Wireless Beyond the Third Generation—
Facing The Energy Challenge

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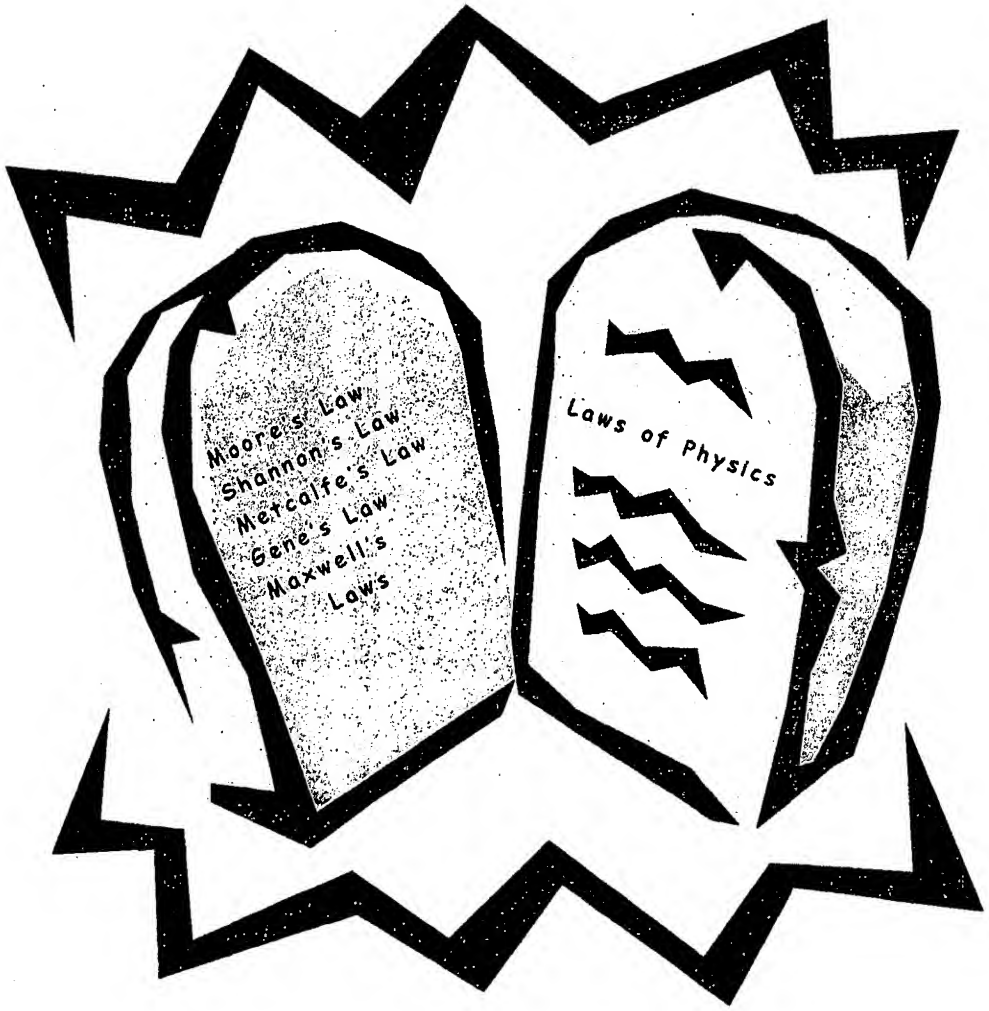
ISLPED 2001, Huntington Beach

It's all about Laws …



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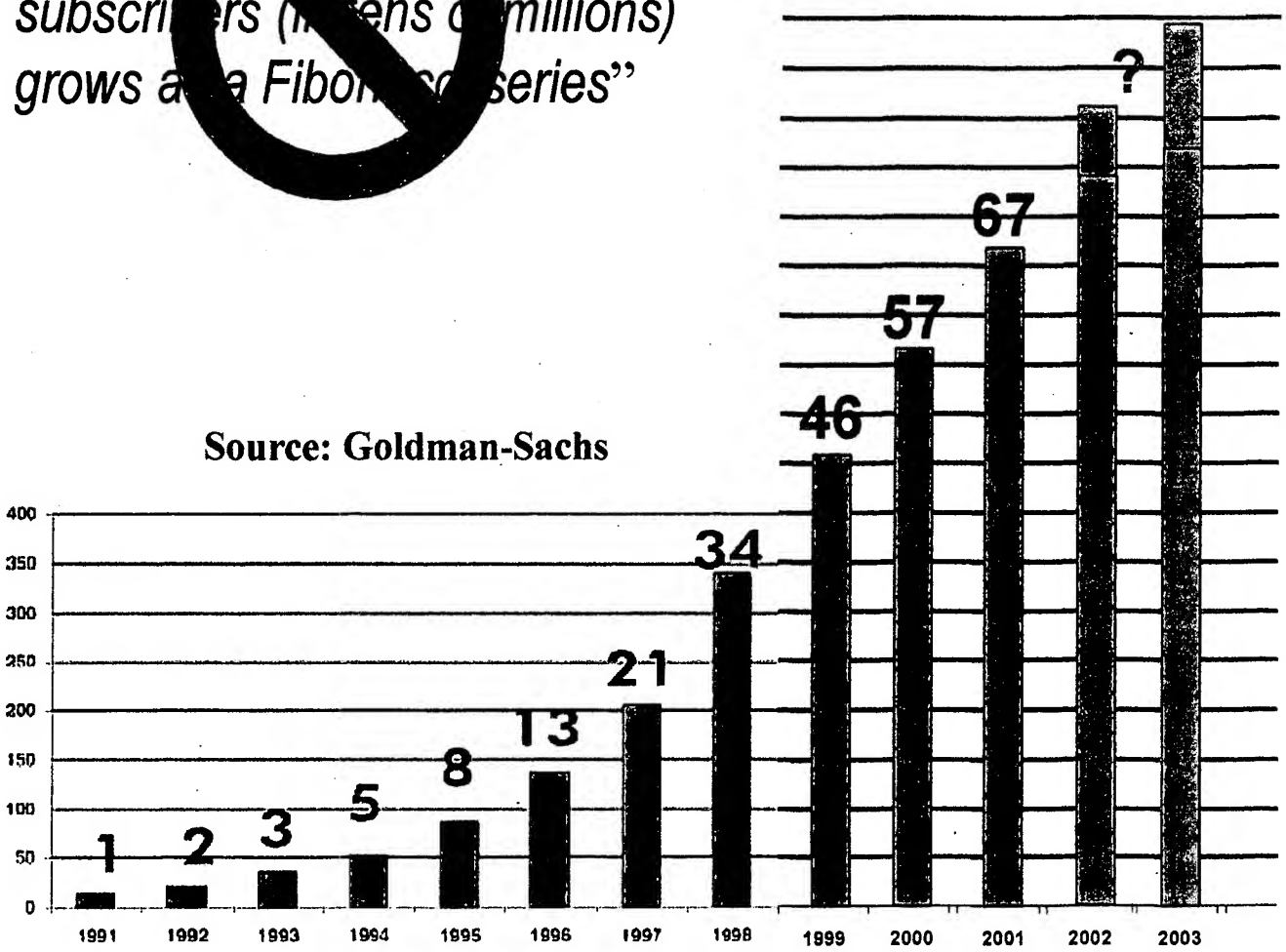
The Fibonacci Law on Wireless Growth

"The nu[illegible] of wo[illegible] wide wireless subscri[illegible]ers ([illegible]tens o[illegible] millions) grows a[illegible] a Fibo[illegible] series"



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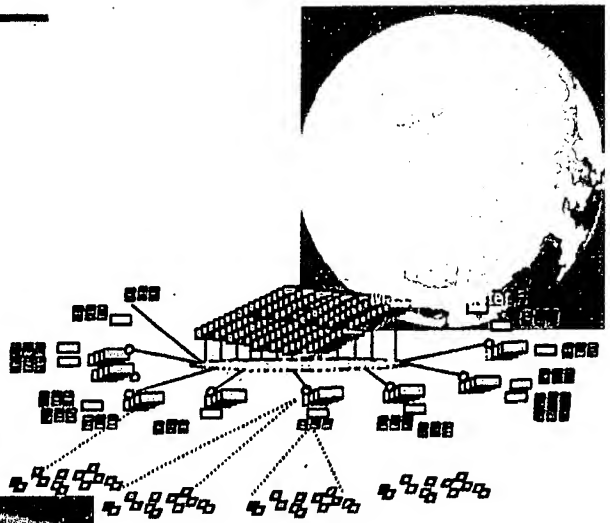
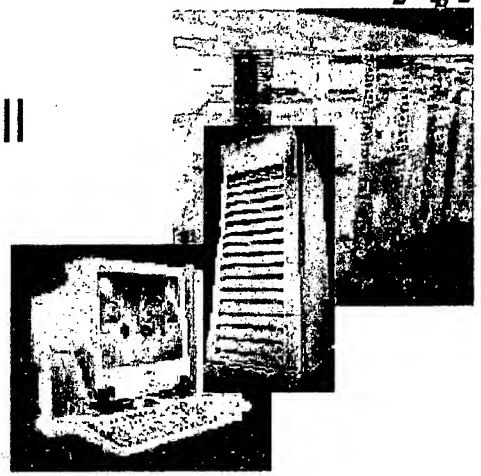
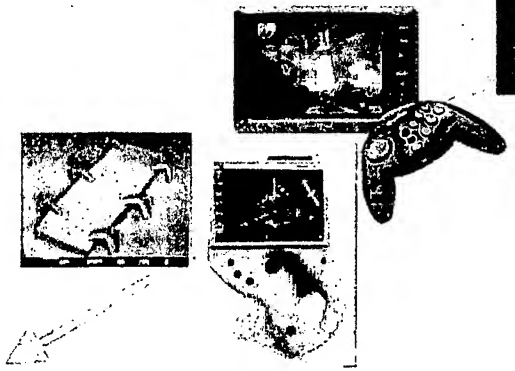
The Shift to Wireless Data— The New Internet

The 1990s:
Conquering the world
The network revolution



The 2000s:
Extending toward the Small
Enabled by integration
(Moore's Law at Work!)
and wireless connectivity





Pre-1990:
Client-Server Systems

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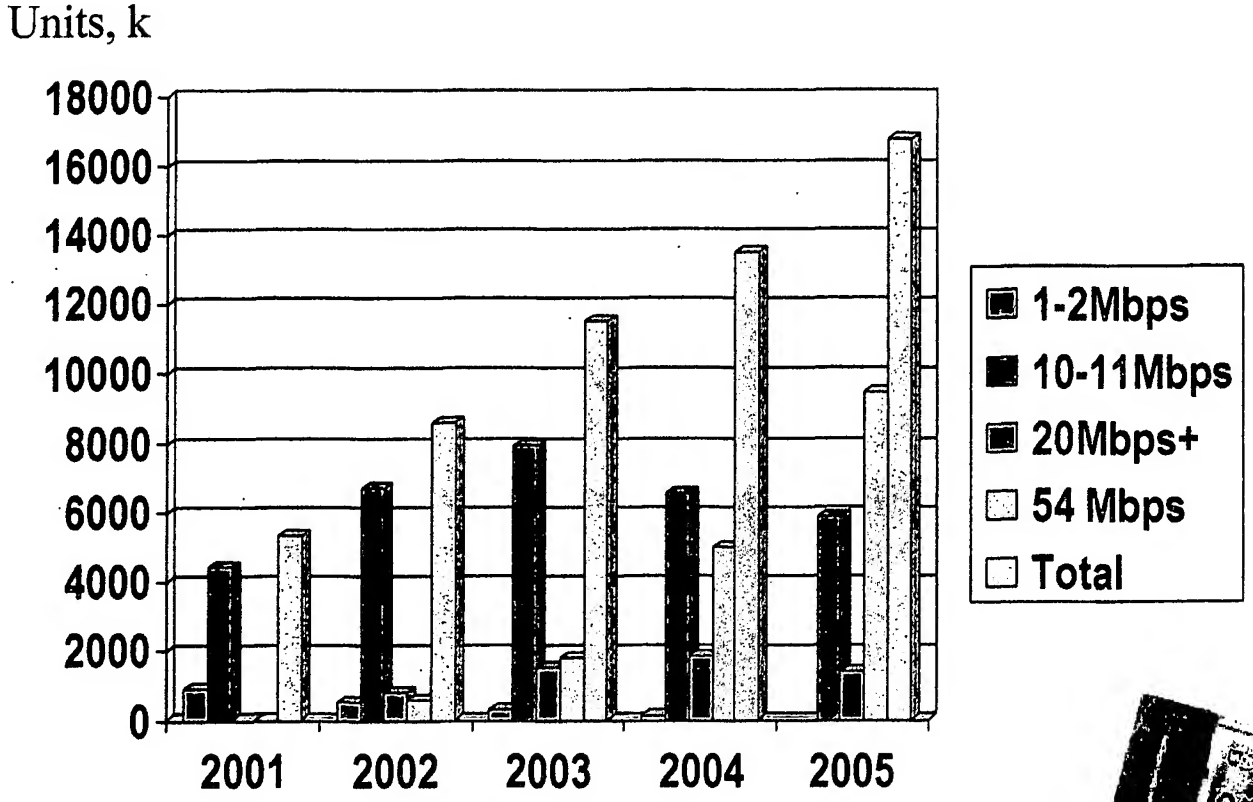
Courtesy: R. Katz, UCB

(Projected) Growth in 802.11 WLAN



Source: Cahners In-Stat 2001

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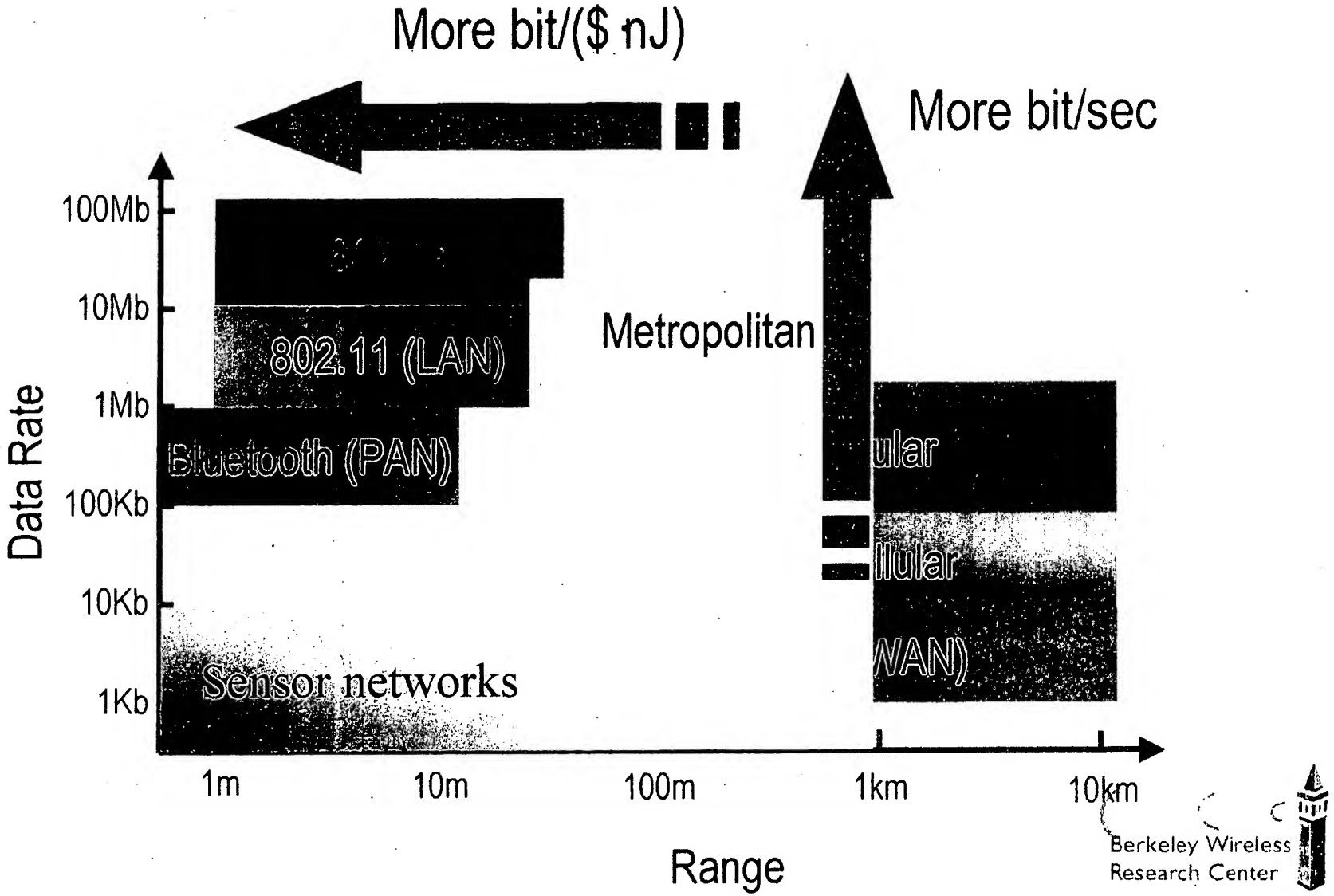
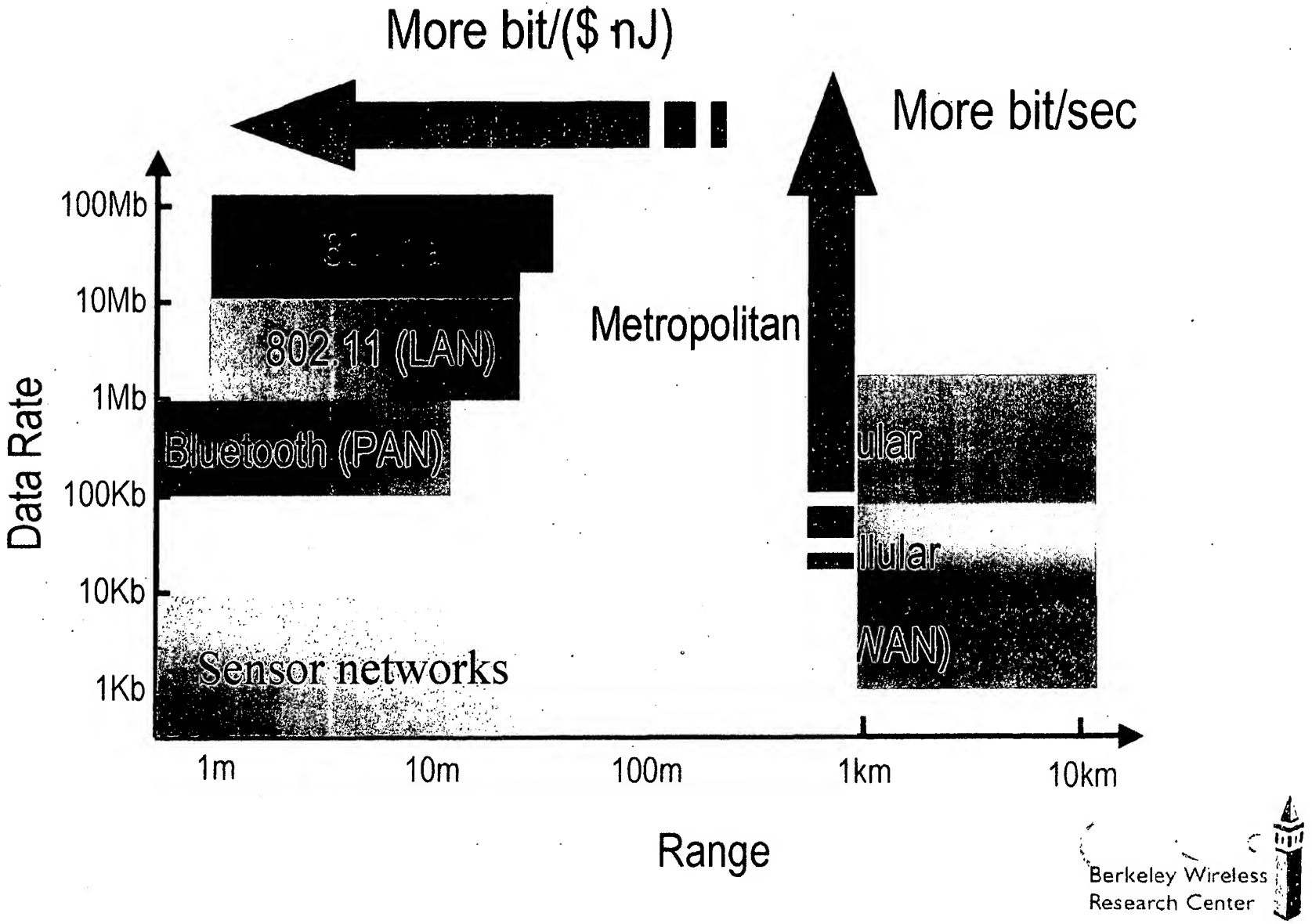
The Evolving Wireless Scene




More bit/($ nJ)
More bit/sec
Data Rate
100Mb
10Mb
1Mb
100Kb
10Kb
1Kb
802.11 (LAN)
Bluetooth (PAN)
Sensor networks
Metropolitan
ular
llular
WAN)
1m
10m
100m
1km
10km
Range
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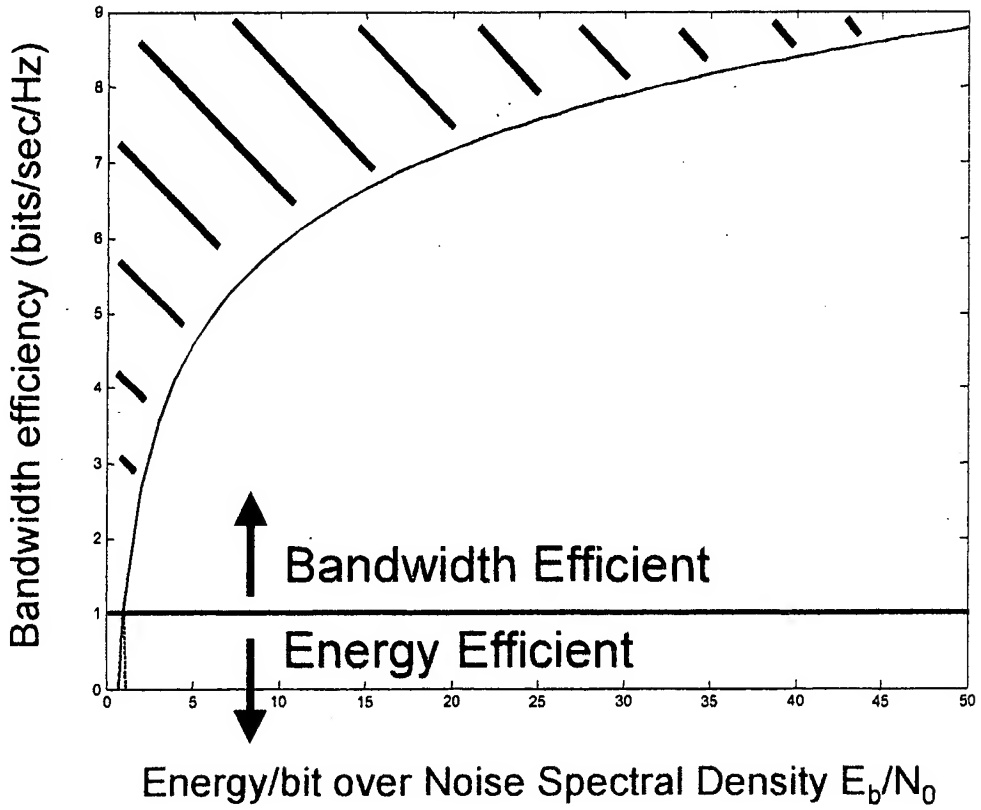
How to Get More bits/sec in a Band-Limited Environment?

The Shannon Bound:

In an AWGN channel, the best bandwidth-efficiency (in bits/sec/Hz) that can be achieved with arbitrarily low bit-error rate is given by



$$bweff \leq \log_2 (1 + bweff * E_b/N_0)$$

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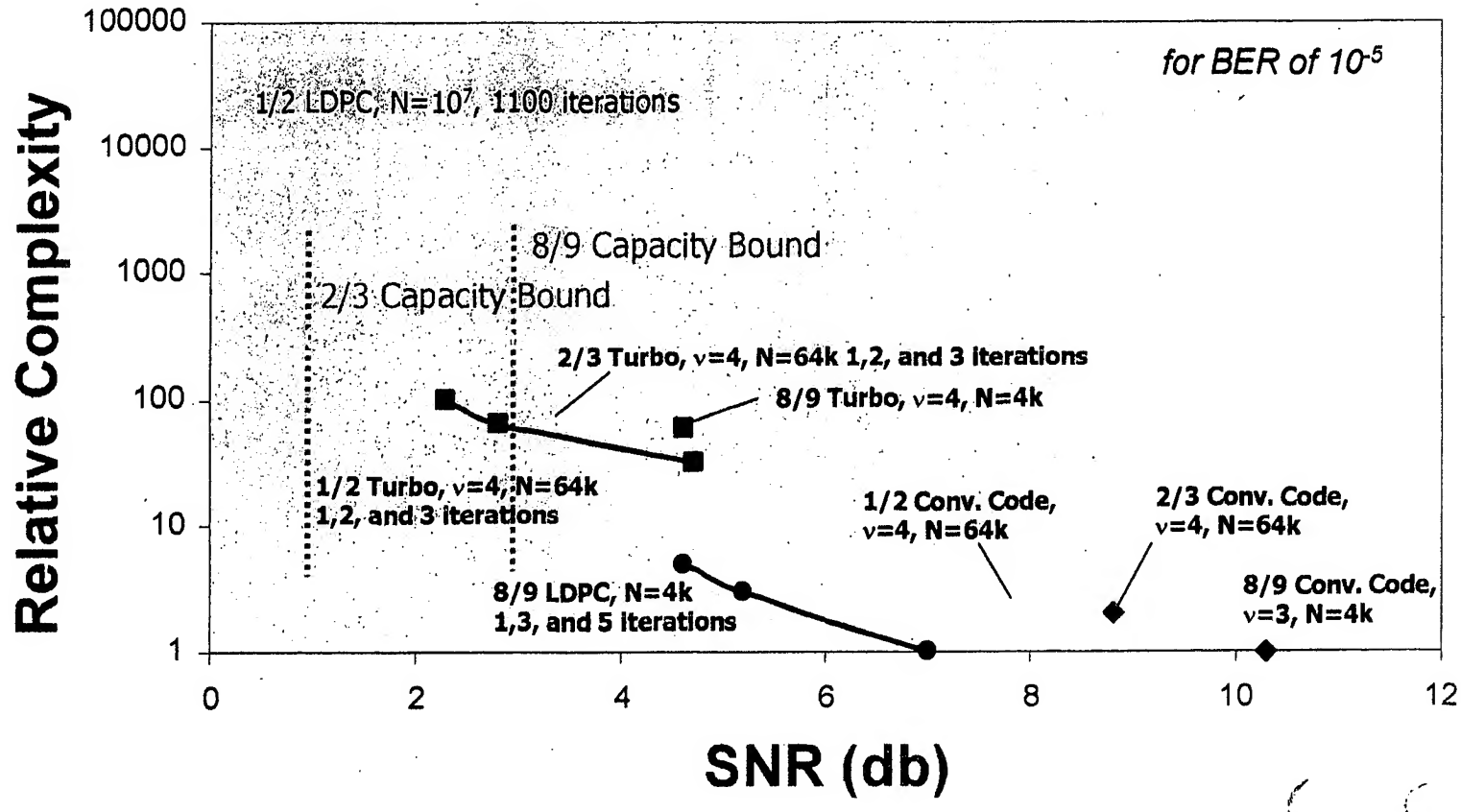
The Cost of Approaching Shannon's Bound

The Bliss and Challenge of Error Coding



Courtesy Engling Yeo, UCB

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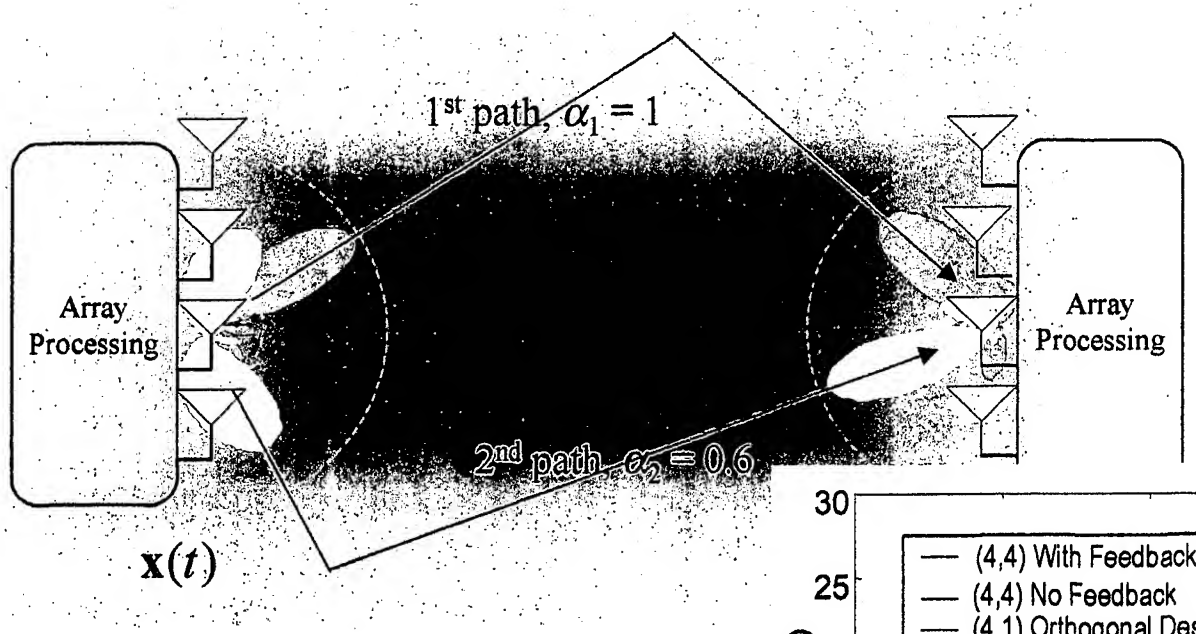
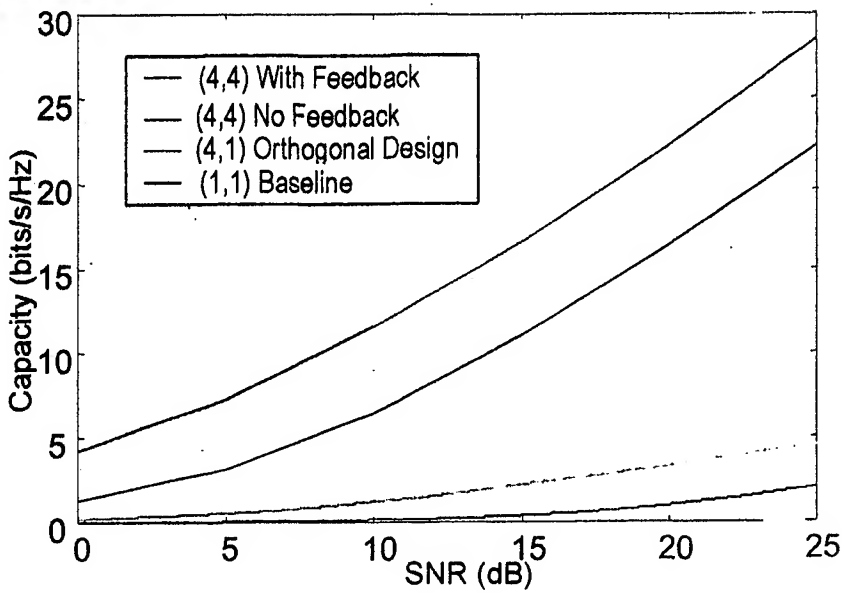
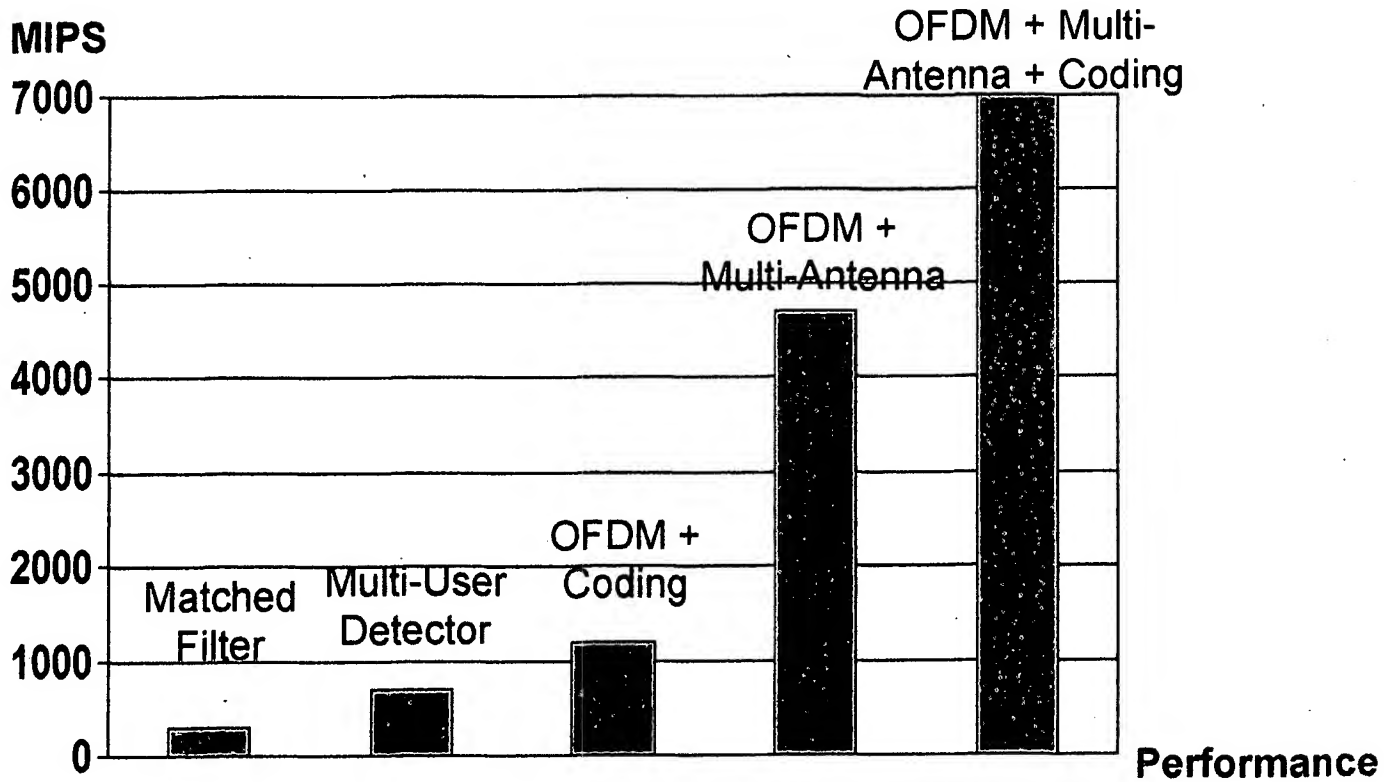
Dealing with Non-ideal Channels (e.g., fading)



- **Multi-antenna approach exploits multi-path fading by sending data along good channels**
- **Results in large theoretical improvements in bandwidth efficiency for fading channels**
- **But...computationally hungry**



The Cost of Dealing with Non-ideal Channels



Data rate per user	0.8 Mb/s	1.6 Mb/s	1.9 Mb/s	3.8 Mb/s	5.6 Mb/s
Spectral efficiency	0.9 b/s/Hz	1.8 b/s/Hz	2.1 b/s/Hz	4.2 b/s/Hz	6.3 b/s/Hz

* Assume 25 MHz bandwidth and 28 users

Source: Ning Zhang, UCB

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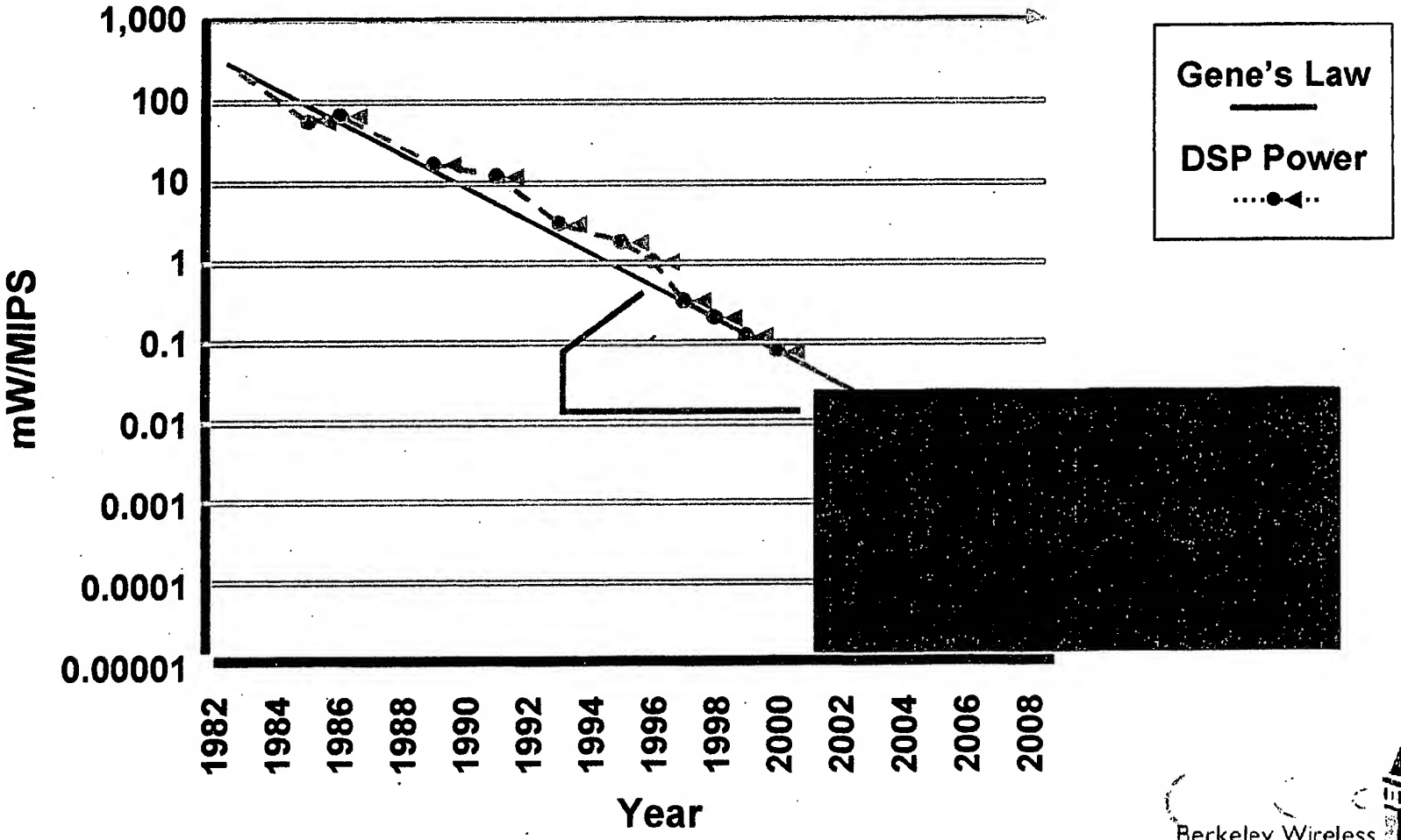
Compelling Wireless Implementation Issues

- **A Ferocious Quest for Performance**
  - Driven by the hunger for bits/sec
  - Outstripping the technology evolution
- **With a Premium on Reduction in Energy Consumption**
  - The compelling argument behind wireless is its untethered nature
  - Power consumption key impediment to penetration of new services
  - Energy sources on slow evolutionary path (5%/year)

What Technology Offers Us
Gene (Frantz)'s Law



Source: Gene Frantz (TI)

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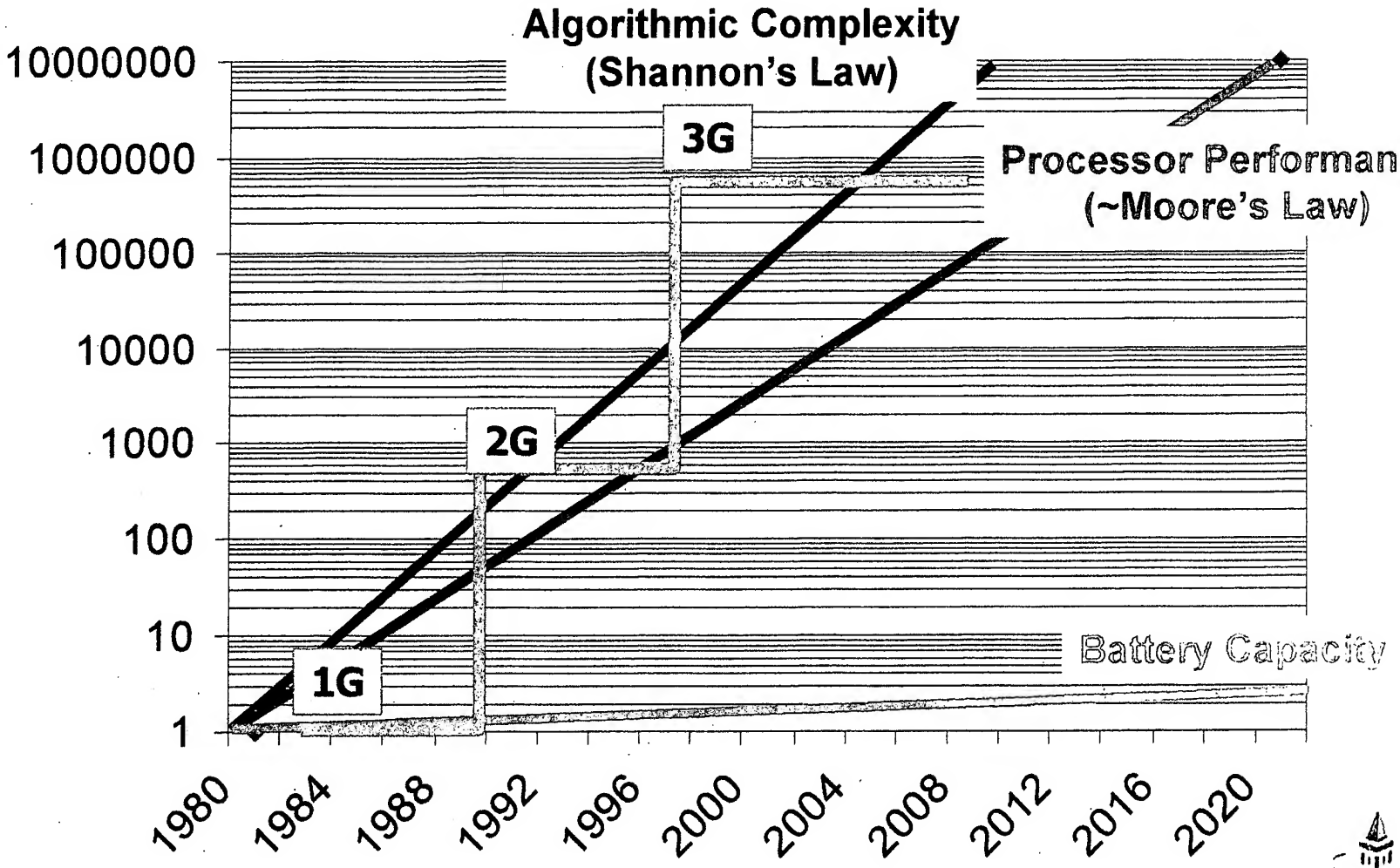
Shannon beats Moore beats Chemists



Courtesy: Ravi Subramanian (Morphics)

The Need for Flexibility

- **Cost-of-design issues point towards component reuse**
  - Design complexity impacts time-to-market
  - Physical effects increase verification costs and design risk
  - NRE of new designs is increasing significantly (mask making, fab cost)
- **Multi-standard has become a must in the diverse wireless landscape**
- **Adaptive solutions lead to better spectral utilization**
- **A wide variety of unpredictable services**

Towards Fewer, but more Flexible and Reusable Silicon Platforms

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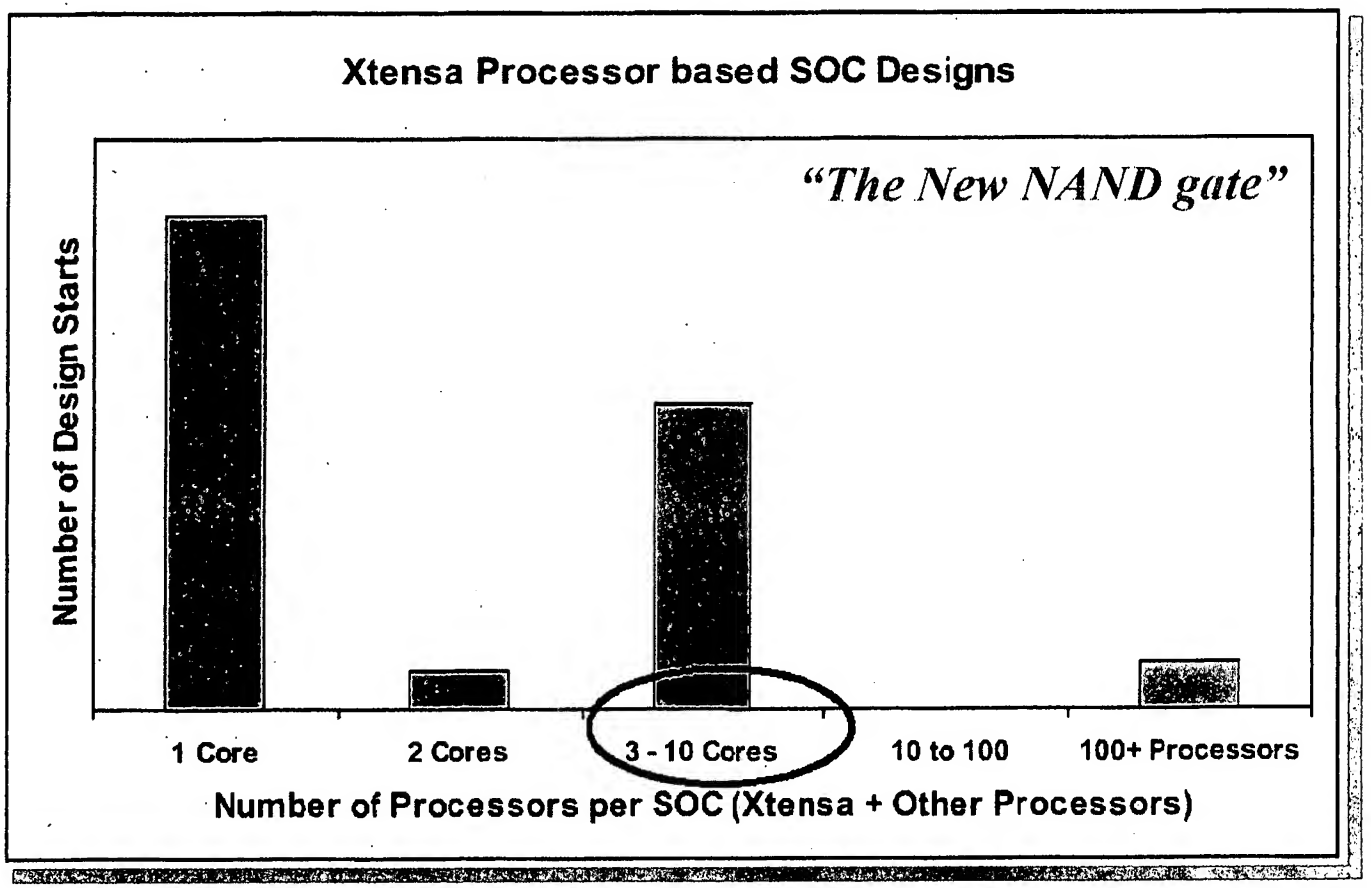
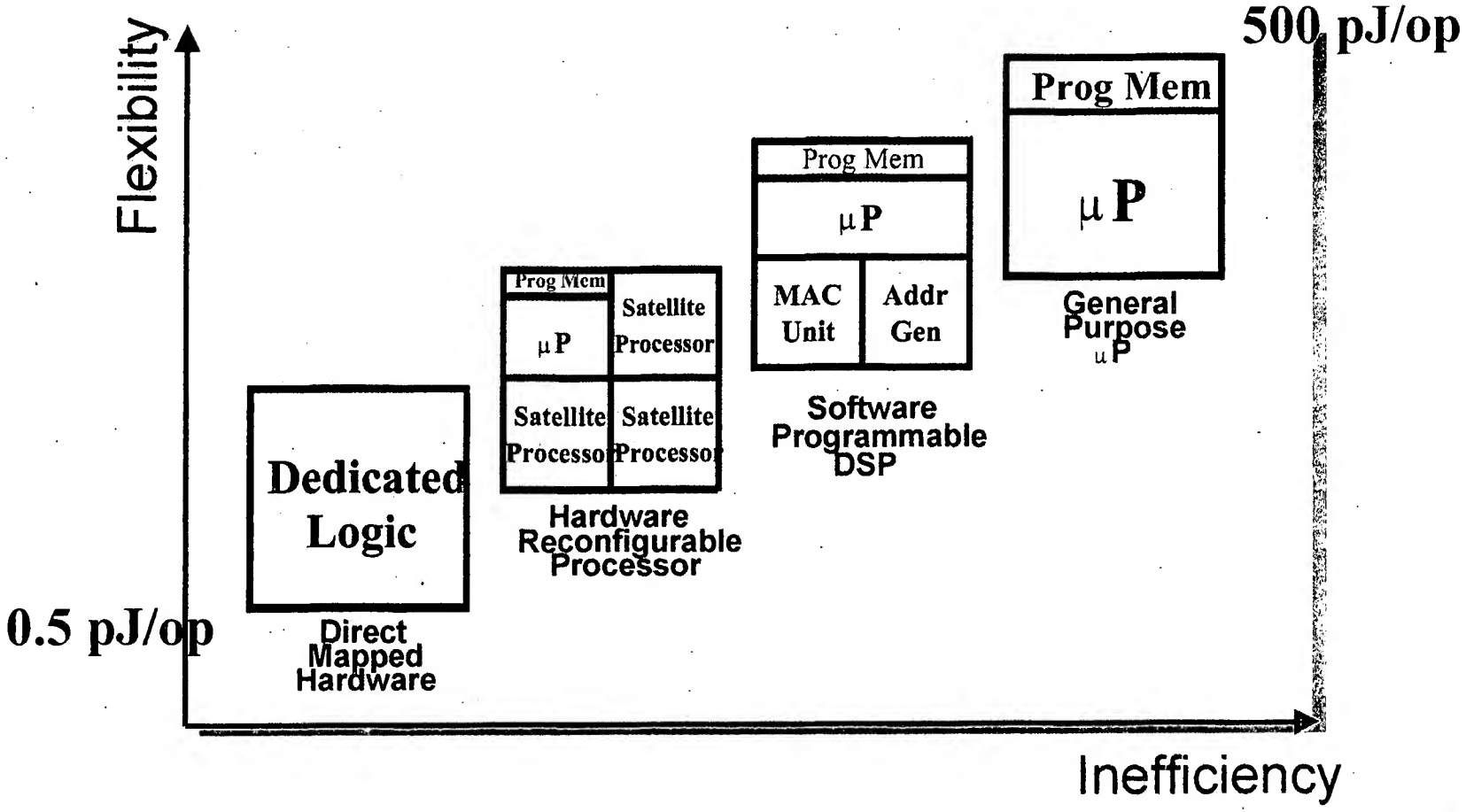
An Attractive Option: Multi-Processor System-on-a-Chip



Courtesy: Chris Rowen, Tensilica

Flexibility Comes at a Huge Cost



3 orders of magnitude!

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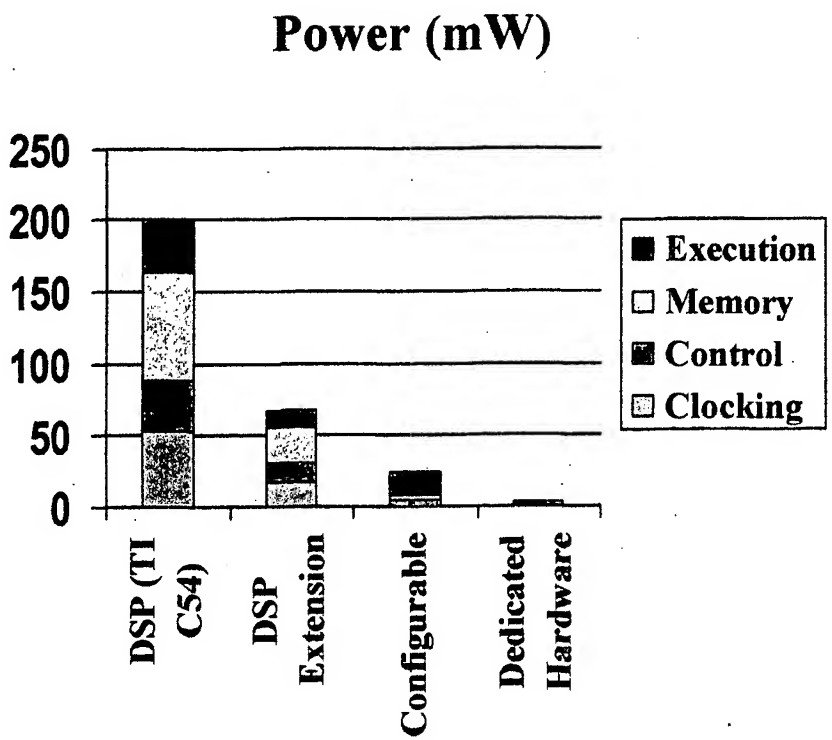
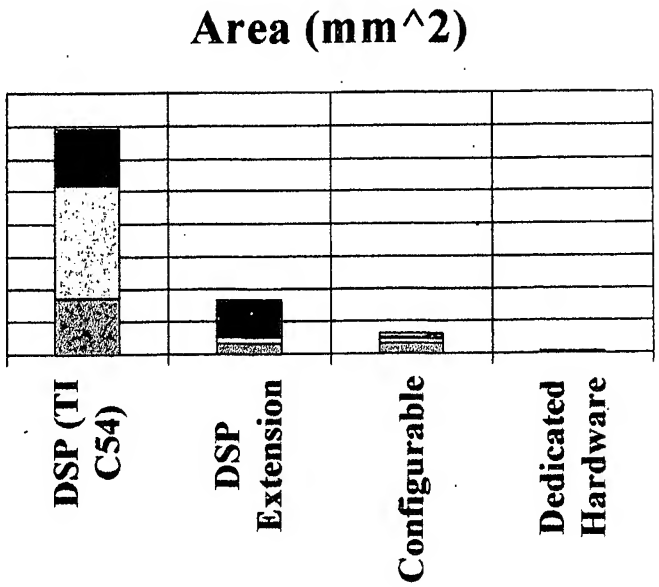
The Opportunity of Configurable Architectures





* Based on the implementations of a multi-user detector

Source: N. Zhang, UCB

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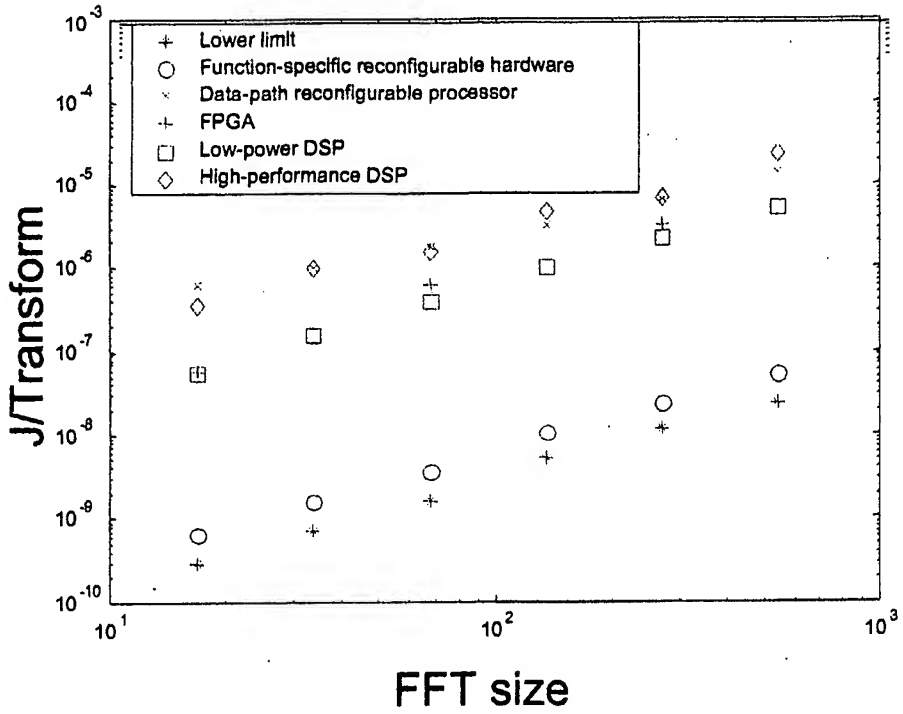
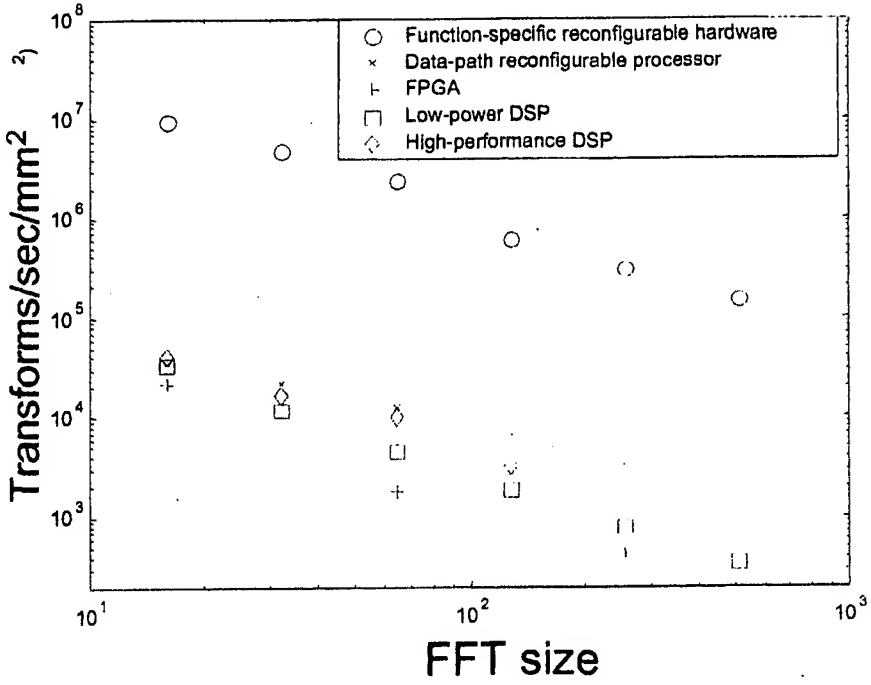
The Opportunity of Reconfigurable—When Does it Work?





Energy and Area Efficiency of Various FFT Implementations

Source: N. Zhang, UCB

* All results are scaled to 0.18μm

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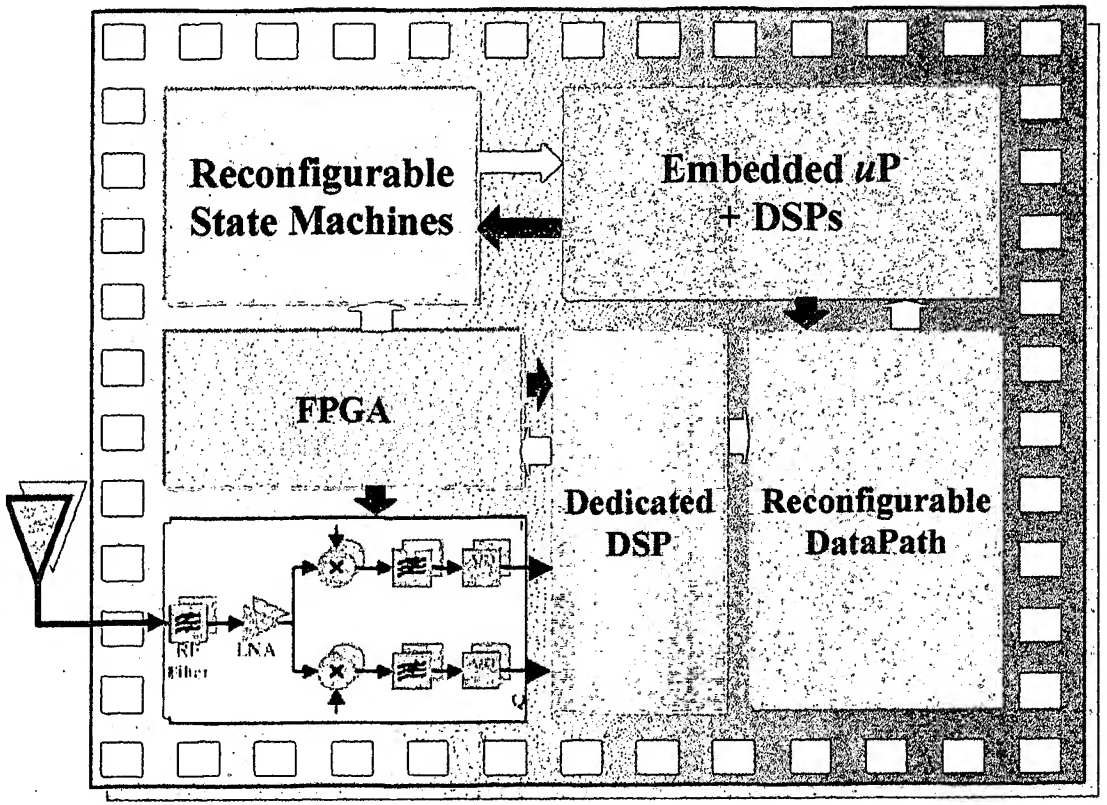
The Ideal "Radio-on-a-Chip" Platform

Combines performance, flexibility and energy-efficiency



- Heterogeneous
- Matches the computational model
- Provides flexibility only where needed and desirable and at the right granularity
- Supports massive concurrency
- Operates at minimum supply voltage and clock frequency

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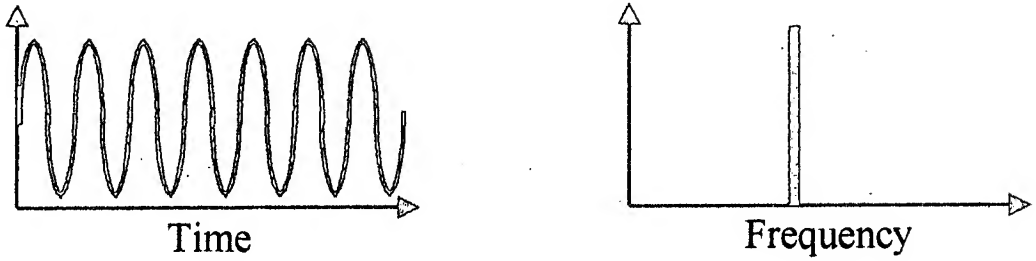
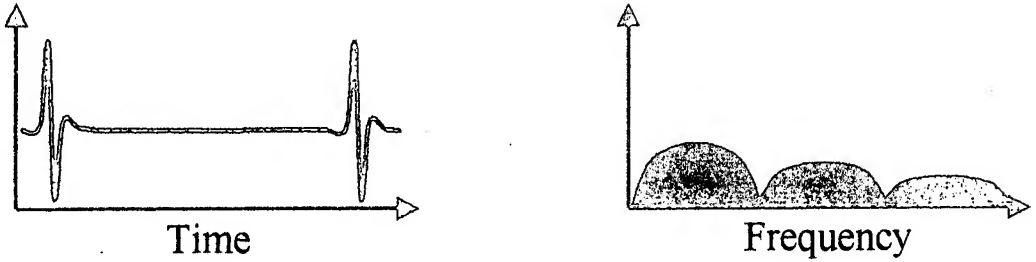
An Orthogonal Approach to Bit/sec— Ultra-Wide Band Radio

Traditional Sinusoidal, Narrowband



Impulse, Ultra-Wideband



Splurge on Bandwidth (> 5 GHz) and Punt on Bit/sec/Hz

Possible advantages: easy co-existence, low-power, simple

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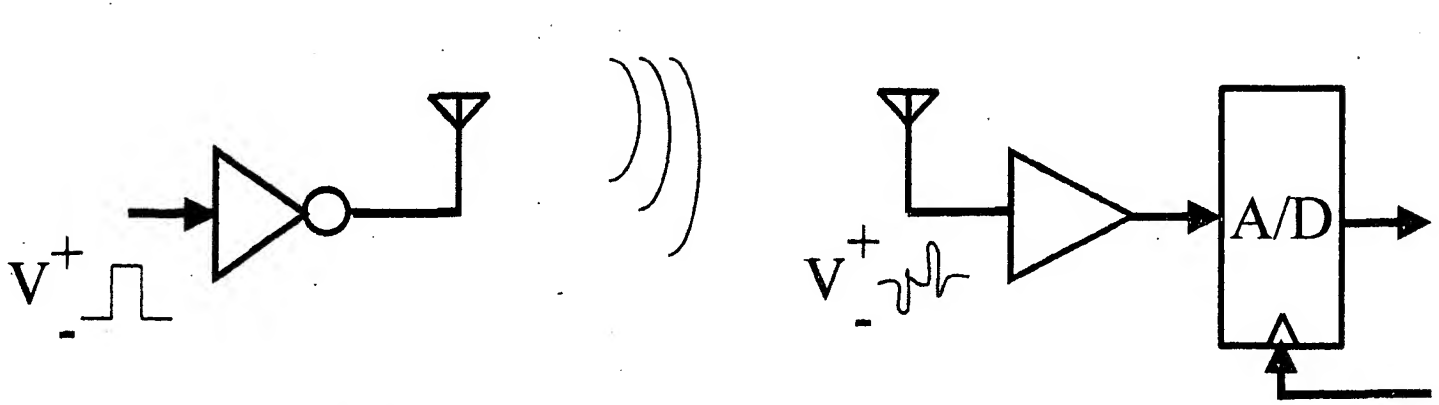
Digital Pulse-Based Radio

Simple Digital Architecture:



- Transmit Only Narrow Pulses (No Carrier Frequency)
- Spread Energy Over Existing Noise Floor

The Architectural Challenge:

Providing accurate timing resolution without high-frequency clocks!

Predicted performance:

100 kbits/sec @ < 10^{-4} bit/sec/Hz and ~ 10 nJ/bit

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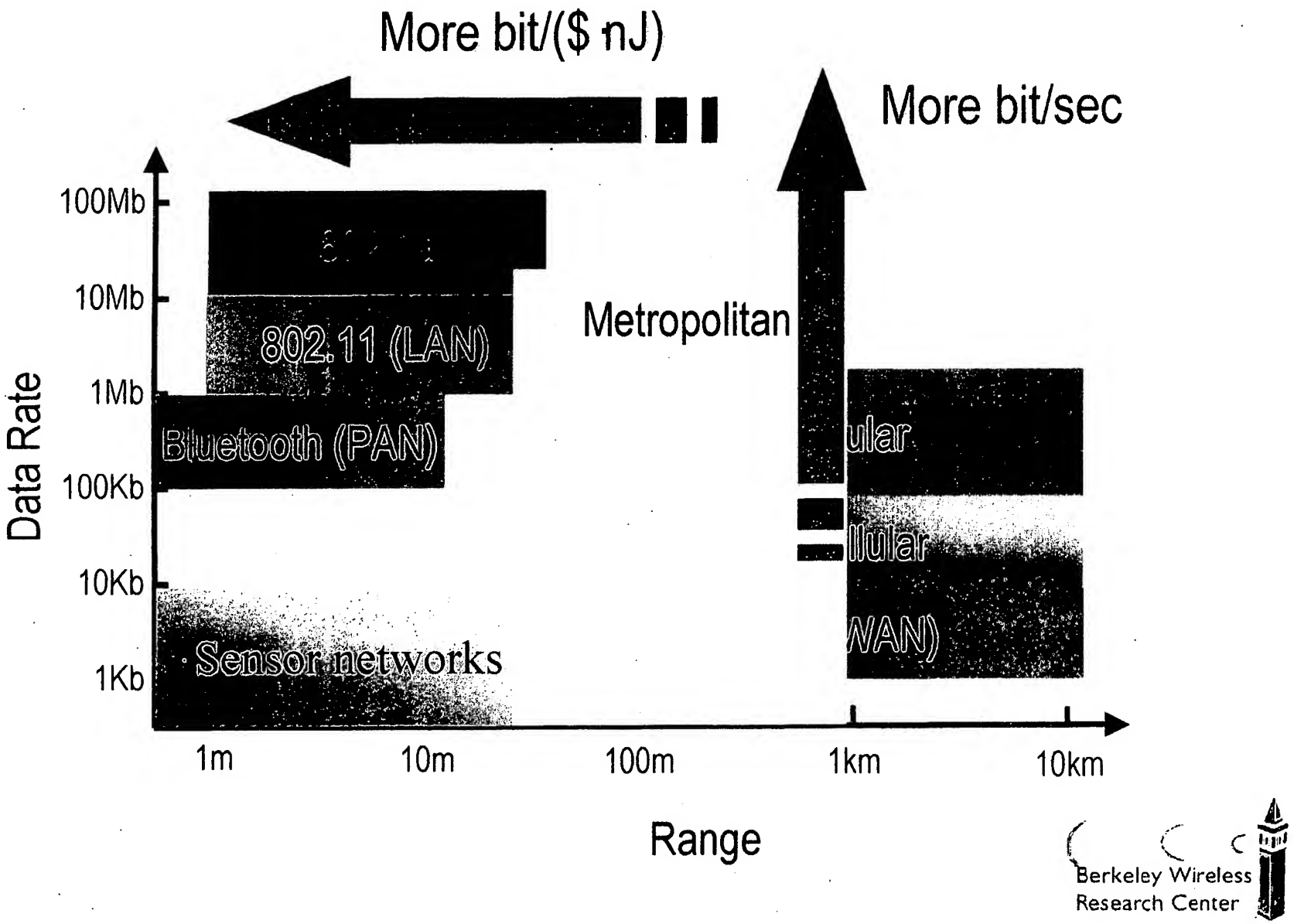
More bit/($ nJ)
More bit/sec
100Mb
10Mb
1Mb
100Kb
10Kb
1Kb
Data Rate
802.11 (LAN)
Bluetooth (PAN)
Sensor networks
Metropolitan
ular
llular
WAN)
1m
10m
100m
1km
10km
Range
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More Bits/(nJ·$·mm³): Wireless Sensor Networks

Pushing the Bounds in Ultra [Small, Cheap, Low-Power]

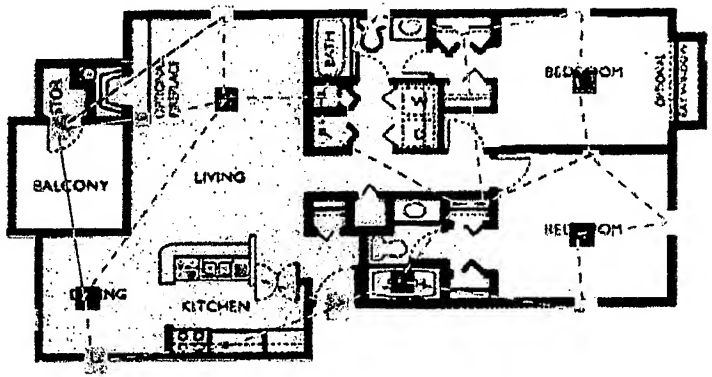
Berkeley PicoRadio's

Meso-scale low-cost radio's for ubiquitous wireless data acquisition in sensor/actuator networks that are fully integrated and consume less than 100 μW enabling energy scavenging

The Smart Building

Integrated Sensor/Actuator/ Control System

- Improves quality-of-living
- Saves energy
- Provides security
- Helps localizing items
- Extends building-human interface



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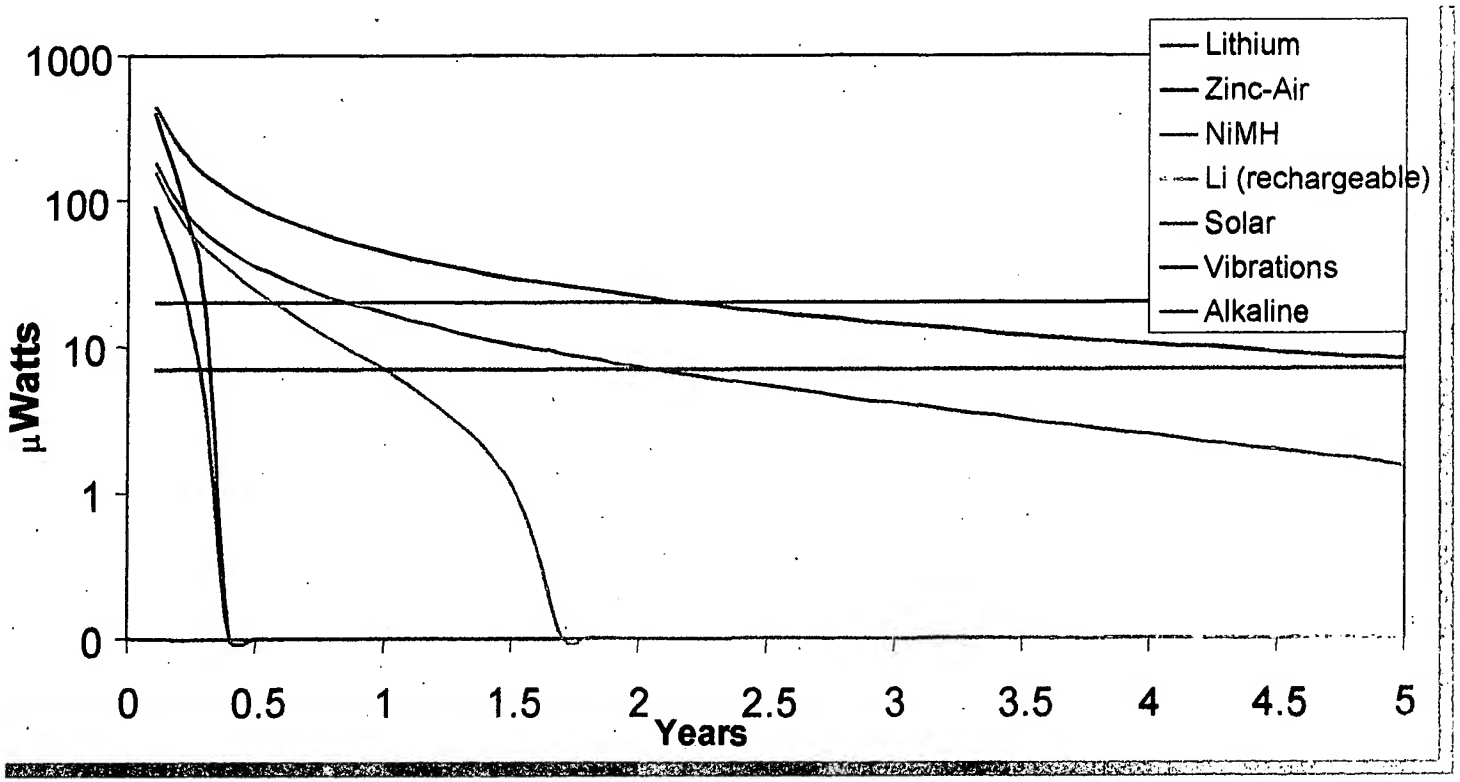
The Energy-Scavenging Opportunity



Battery size: 0.5 cm^3
Vibration: 1 cm^2 piezo-electric
Solar: 1 cm^2 single-crystal

Courtesy: S. Roundy (UCB)

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Opportunity: Metcalfe's Law

" The true value of a network increases as the square of the number of users on the network"

A Variant: Jan's Law

" The power efficiency of a wireless sensor node increases as the square of the number of nodes in the network (or is proportional to the node density)."

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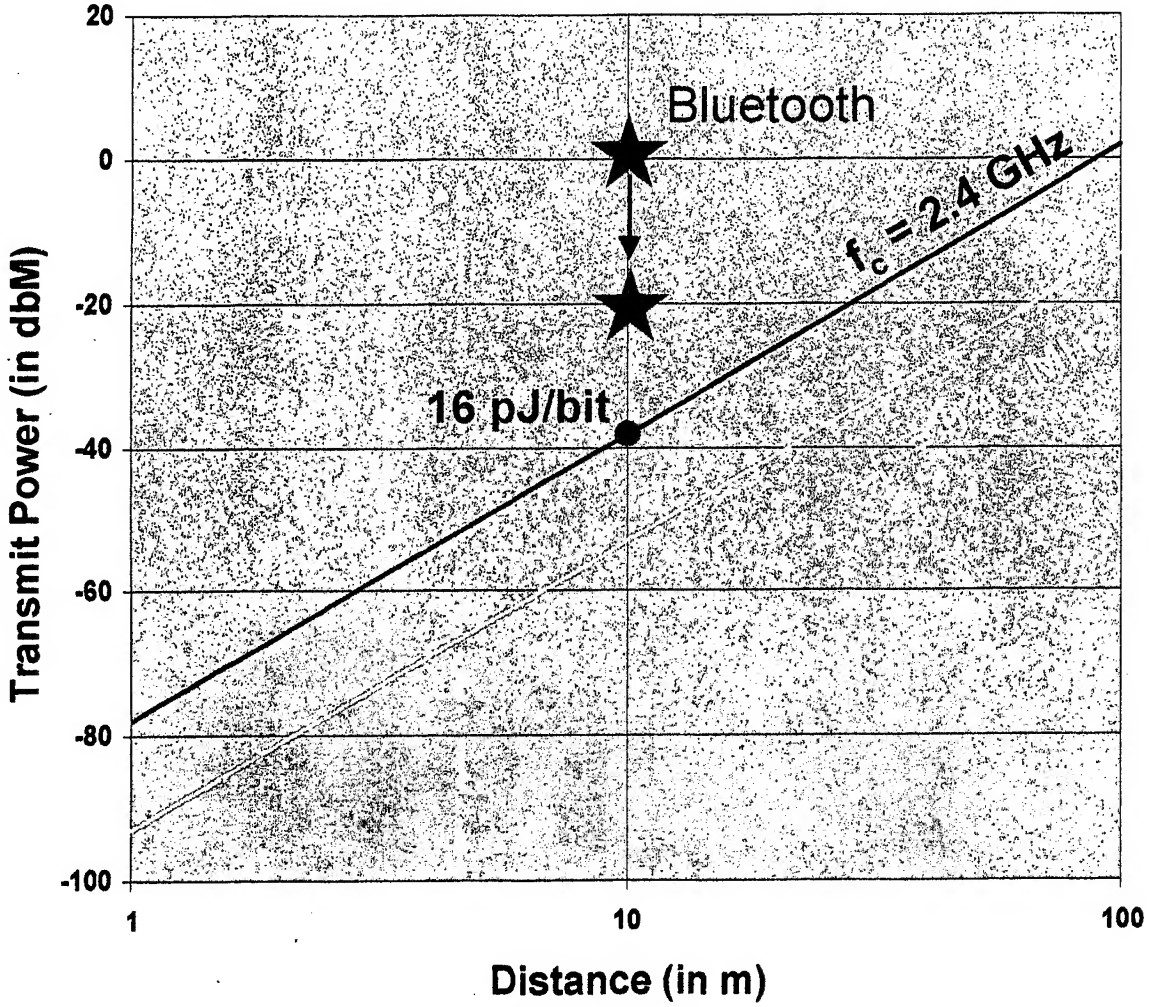
Addressing the Communication Cost



(assuming d^4 path loss of and 10 kB/sec data rate)

- **Minimum required transmit power increases as d^4 due to ground wave and multi-path**
- **Increasing carrier frequency costs 20db/decade**

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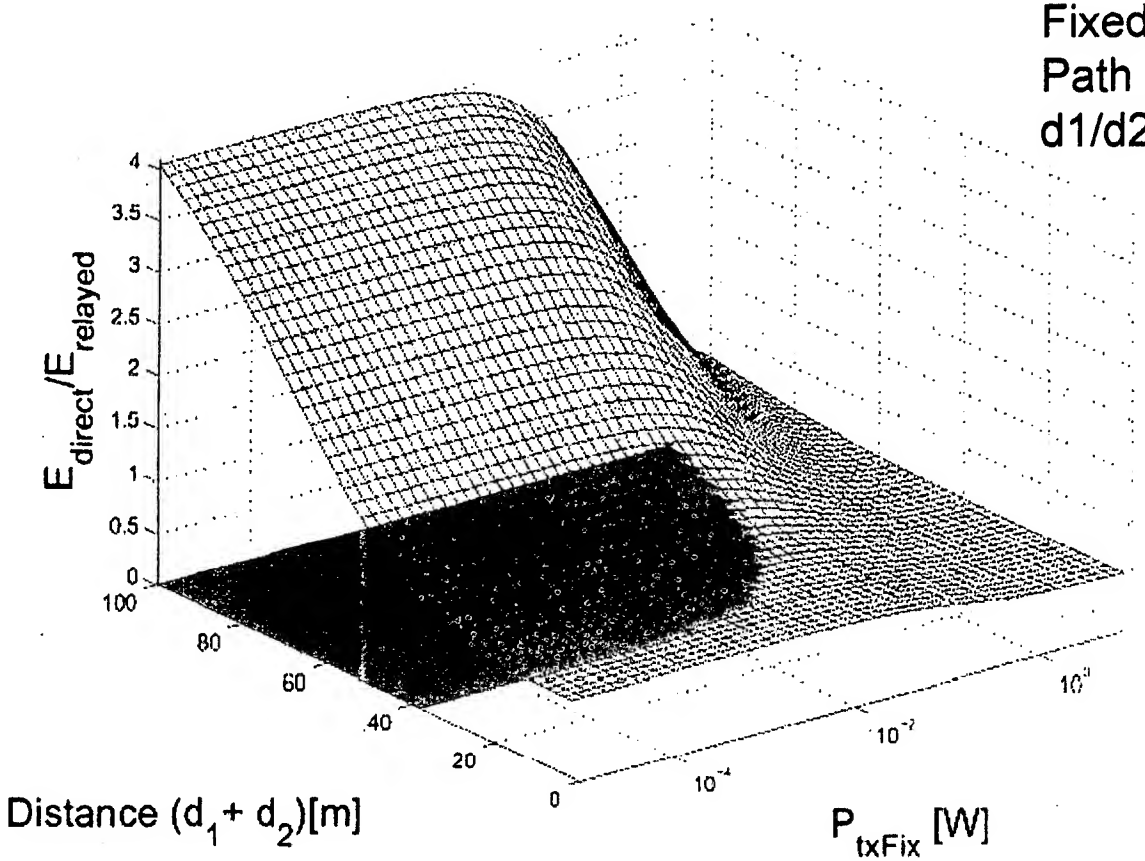
Adding a Single Relay Point in a Wireless LAN

Bit-rate: 6 Mb/sec
Packet Error Rate: 1%
Fixed Receiver Power: 100 mW
Path Loss Exp.: 3.8
d1/d2 =1



Reduces energy/bit up to 4 times!

Source: M. Kubisch and H. Karl, TU Berlin

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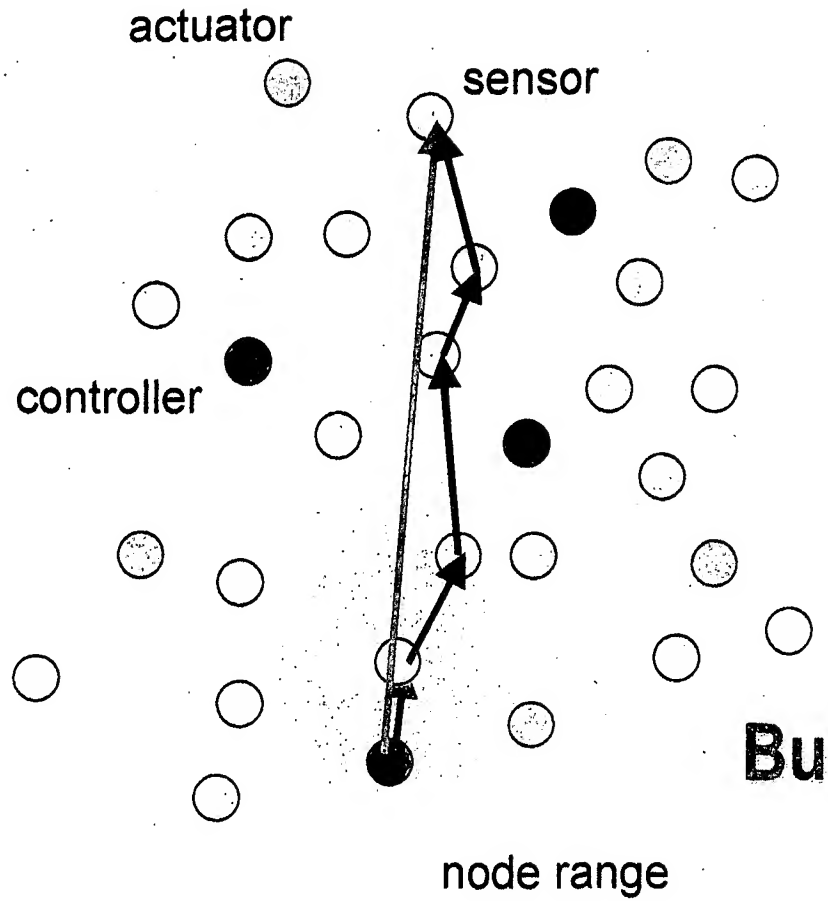
Trading-off Latency for Energy: Self-configuring Multi-hop Networks



- **1 hop over 50 m**
  1.25 nJ/bit
- **5 hops of 10 m each**
  5×2 pJ/bit = 10 pJ/bit
- **Multi-hop reduces transmission energy by 125!**

But …how to ensure fairness?

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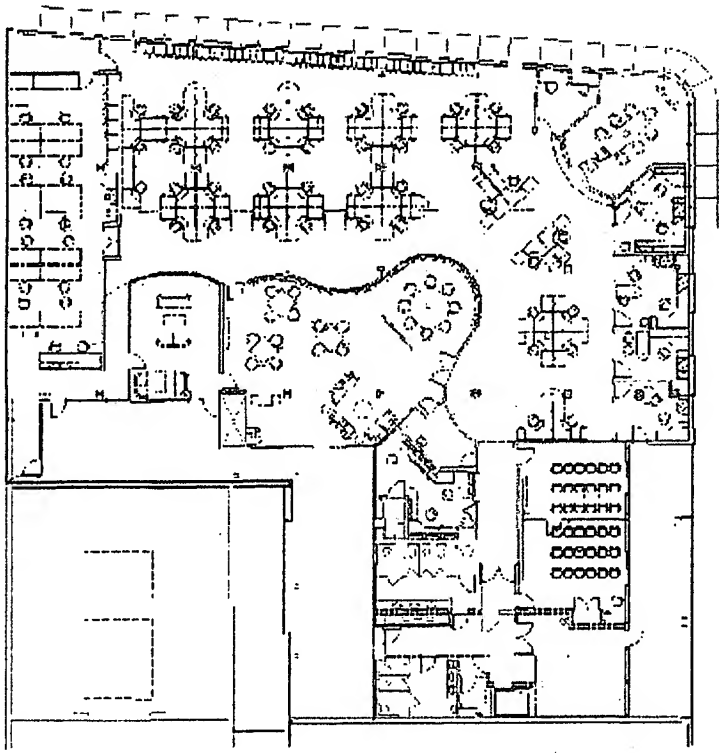
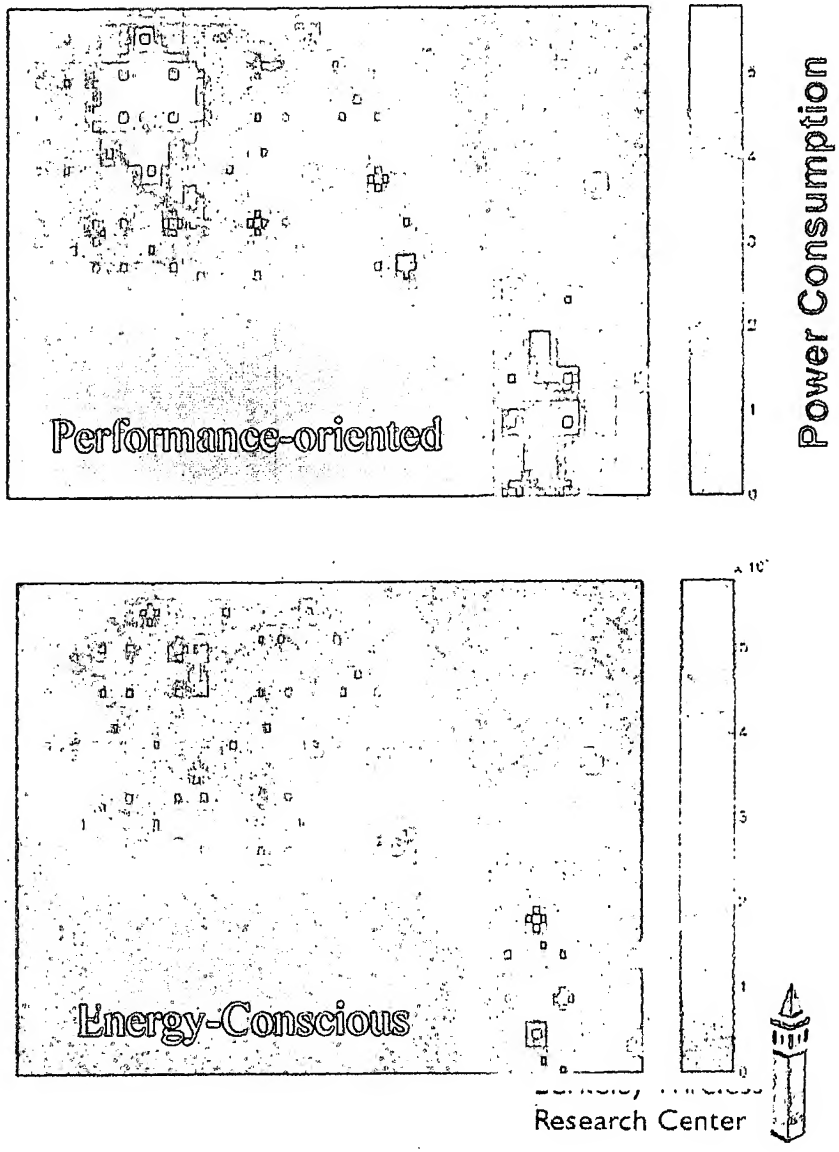
Energy-Conscious Networking

Simulated Energy Dissipation in Sensor Networks (BWRC)



Source: R. Shah (UCB)



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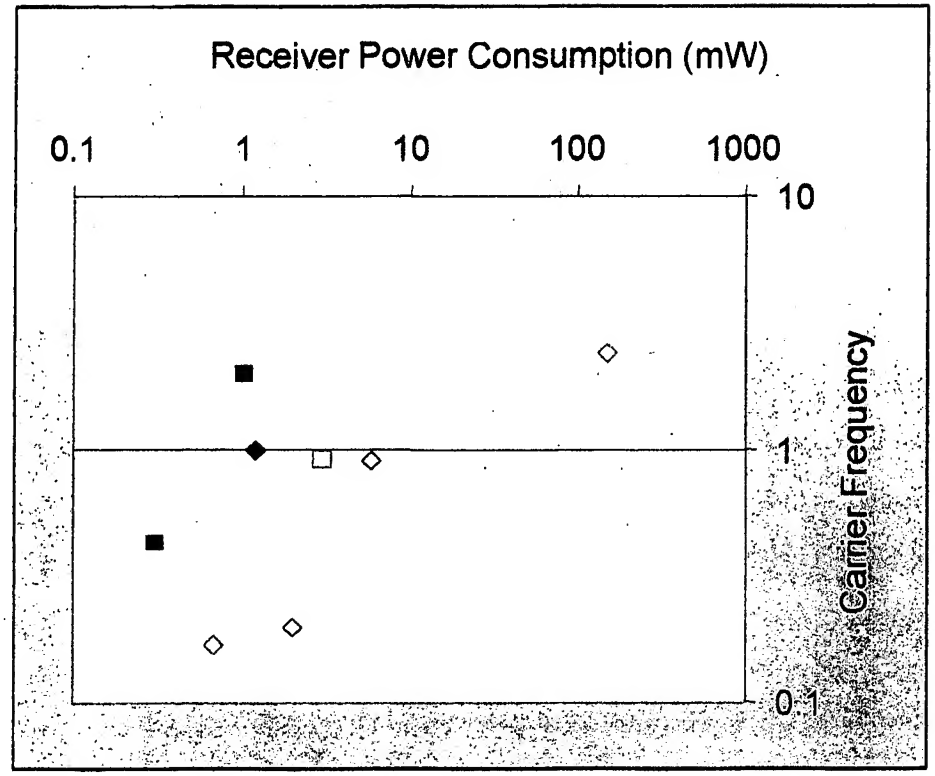
The Sensor-Node RF Challenge



- **Increasing carrier frequency increases power dissipation**
  - Mostly due to higher speed active components (synthesizers, mixers, A/Ds)
- **But enables higher integration**
  - Smaller sizes of passives ands antennas

Rx power consumption versus carrier frequency for a number of low-data rate, small-distance RF implementations (all operate in Shannon's "energy-efficient zone")

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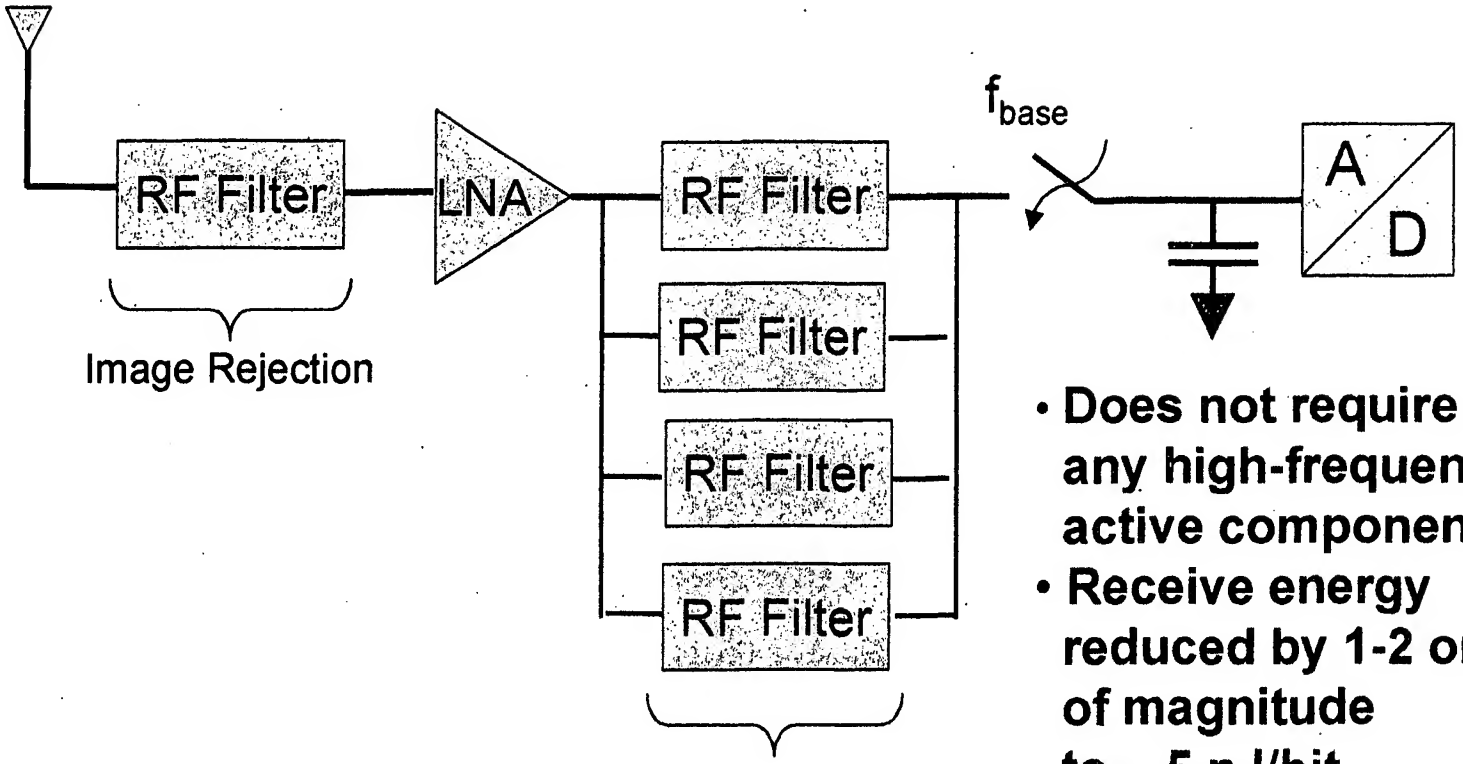
Eliminating most High-Speed Components

Sub-sampling receiver with passive frontend



- **Does not require any high-frequency active components**
- **Receive energy reduced by 1-2 orders of magnitude to ~ 5 nJ/bit**

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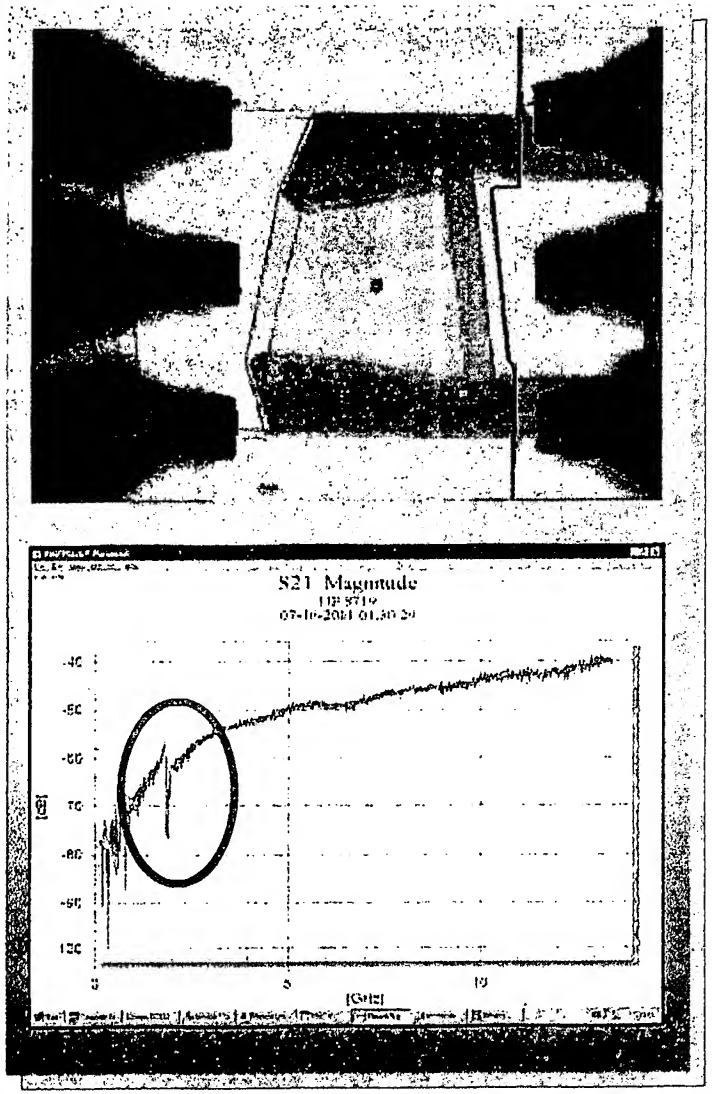
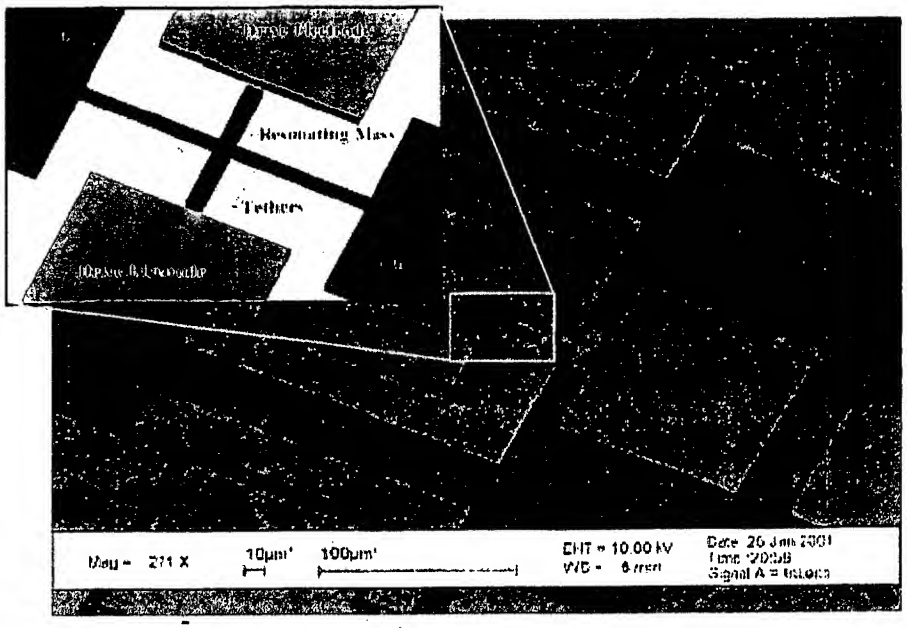
Enabled by High-Q Integrated Filters



Thin-Film Bulk Acoustic Resonators
Q > 1000 @ 2 GHz
(FBAR – Agilent)



RF-MEMS: Poly Si-Ge Resonator

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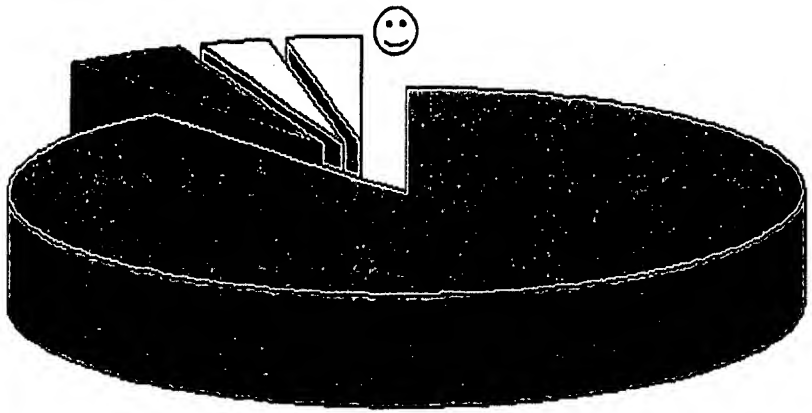
The Importance of Power Management

- **Activity in sensor (data) networks is low and random (< 1%)**
- **Receiving a bit is computationally more expensive than transmitting one**
- **Most Media Access protocols assume that the receiver is always on and listening!**

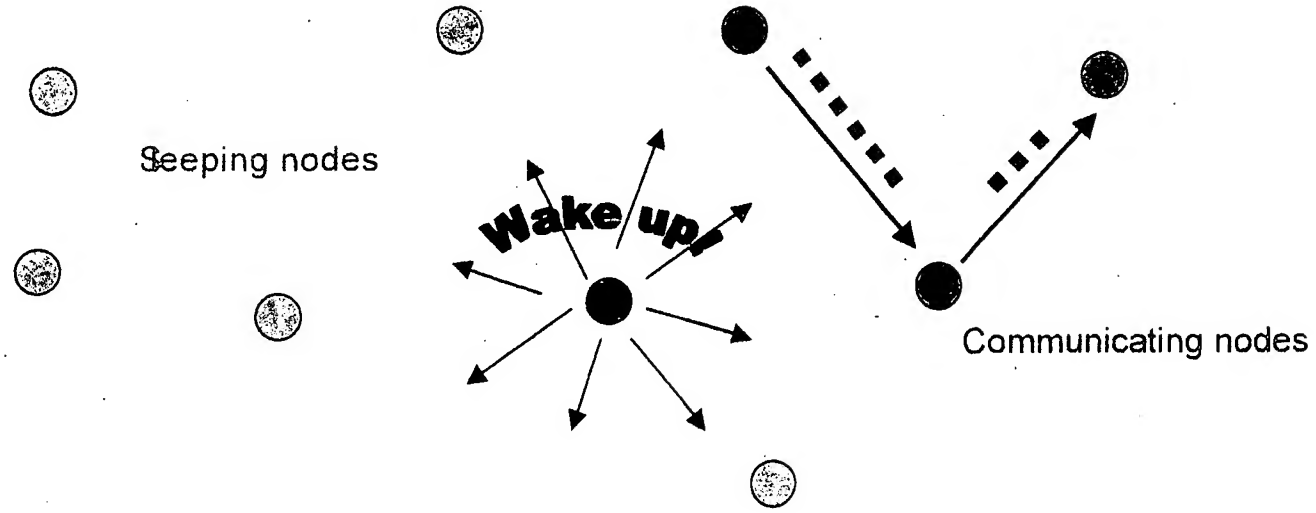


Why not power transceiver up for real events only (incoming data, sensor event, network maintenance)?

Reactive Media-Access Control

Truly Reactive Messaging at the Physical and Media-Access Level

- Power Down the Whole Data Radio
- Reduces Monitoring Energy Consumption by 10^3 Times
- Wakeup Radio Powers Up Data Radio for Data Reception



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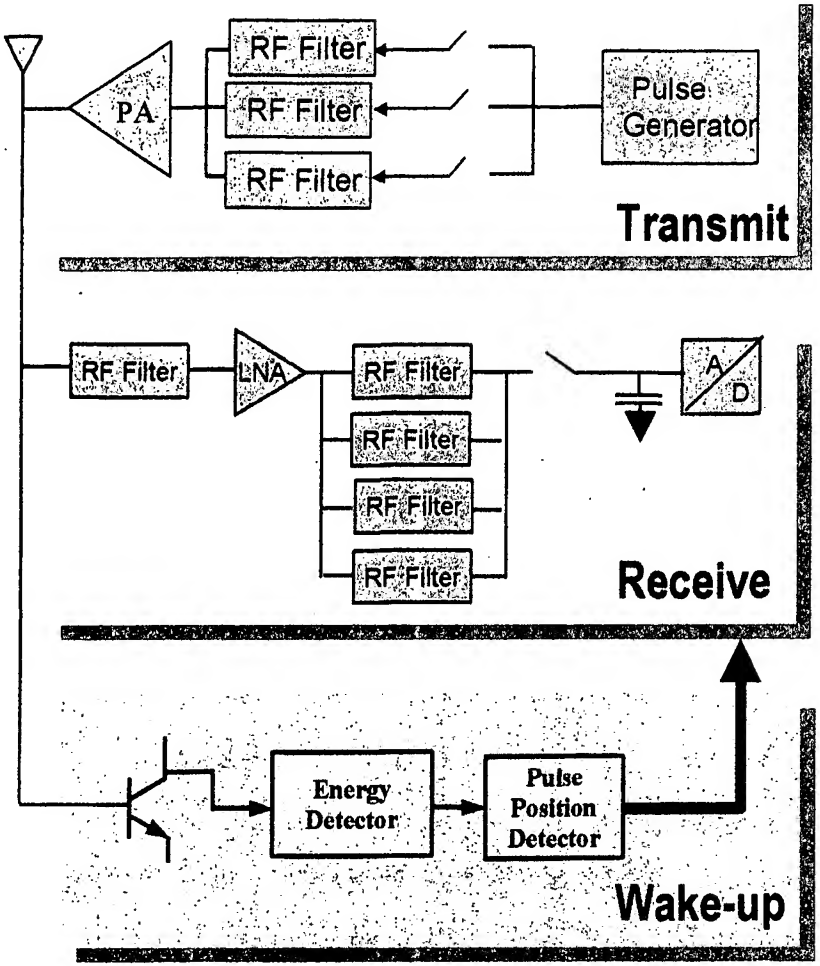
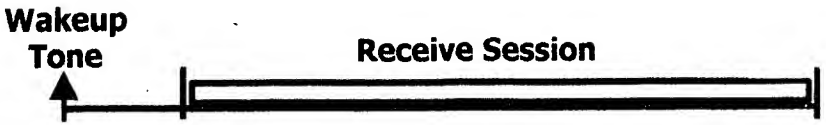
The Wake-up (Reactive) Radio



- **Always running**
  - Super low power: 10^{-4}~ 10^{-3} active mode power
- **Data radio shut down when idle, and powered up by wake-up radio**
- **Receiver response time: < 10ms**



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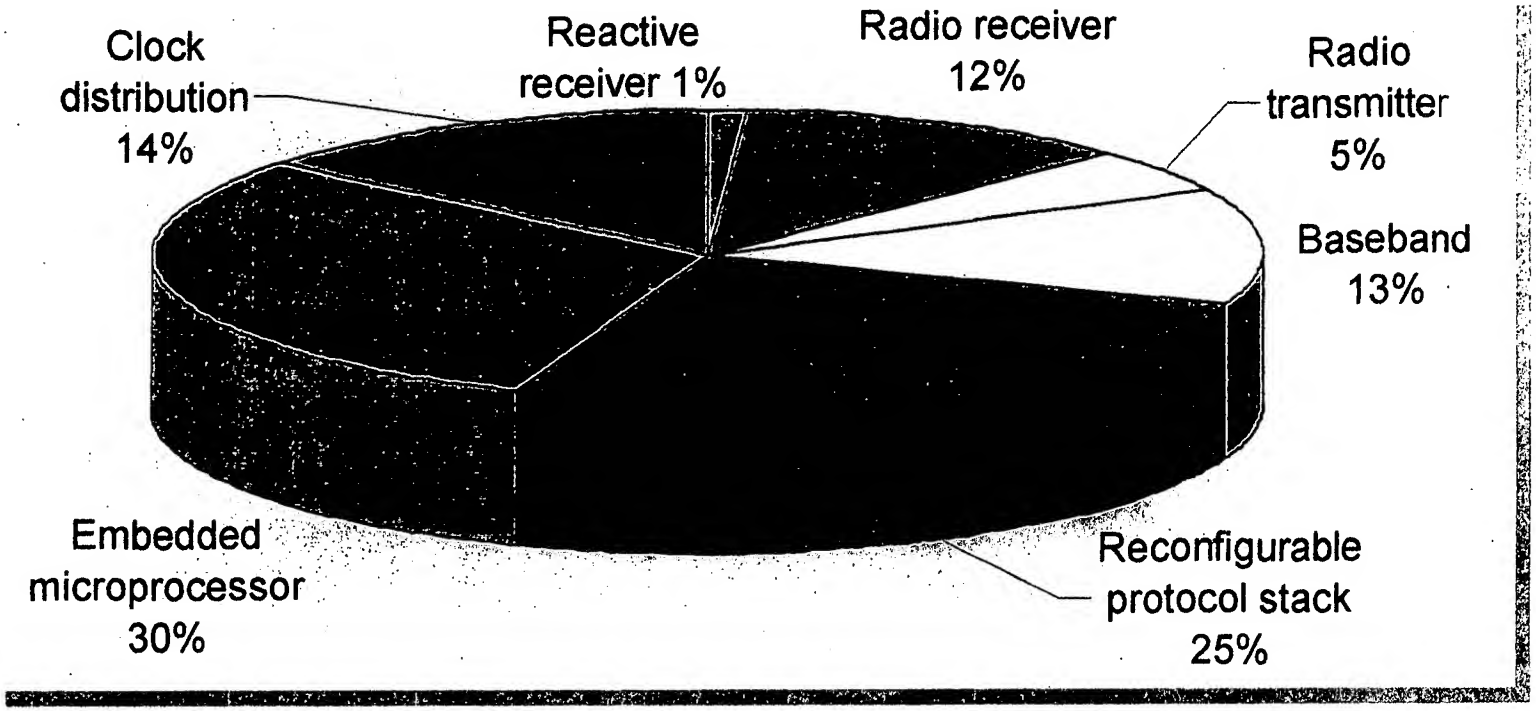
What it Ultimately Boils Down To— Power-Profile of PicoRadio (Projected)



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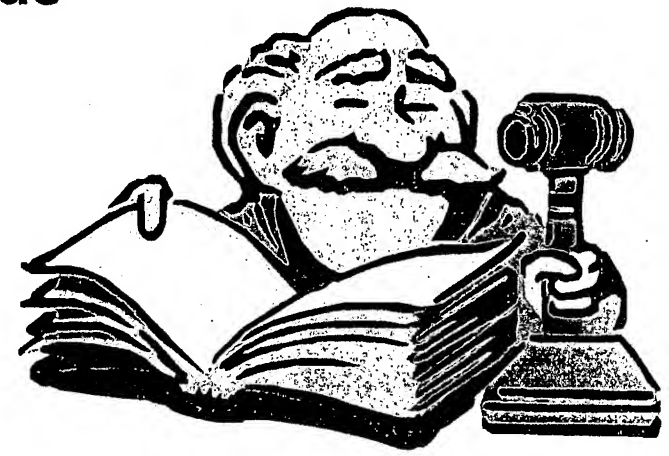
Summary/Perspective

- **Both the bits/sec/Hz and the bits/nJ quests create formidable energy challenges**
- **Keep your eyes open for innovative, orthogonal approaches that re-stack the cards**
  - There is a whole lot of unexplored land available > 10 GHz
- **In the end, it are the laws of physics that provide the ultimate bounds**



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